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Developing Models of Road Tunnels with Petri Nets

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Abstract

1200 road tunnels have been built in Norway's European, national, and county road networks. Length, incline, and traffic volume vary, and it may cross through fjords or mountains, have one or two runs, and be near or far from populous areas. Variation is high, and the development of new road tunnels is a never-ending process; as a result, new records are being established, the country's transportation systems and infrastructure are growing more complex, and more people rely on driving in tunnels.

As science and technology advance, new solutions are developed to improve tunnel safety and prevent accidents by boosting safeguards. Several studies have been undertaken to investigate the causes of traffic accidents and create preventative methods. Most accident occurs on open roadways. However, tunnels tend to cause serious accidents especially in the inner zone.

This thesis used Petri Nets. It's a flexible and easy-to-use network that helps explain, analyse, and simulate complex systems using real-time data so you can better understand the problem or system. The suggested model offers a simple user interface and requires little math. The paper included a GPenSIM model and a brief review of tunnels and vehicle traffic.

Different models are crated in this thesis with varying complexity. The last model simulates a tunnel with a roundabout inside. Here data from the Norwegian Road Authorities are used to see of the model can simulate a realistic scenario. The data shows that the model is performing as expected and that the tunnel manages to deal with the traffic volume during peak hours. The model also allows to change the traffic volume to simulate if the tunnel can handle the additional number of vehicles. As constructed tunnels need to take future traffic volume into account, this simulation feature gives useful insight to the tunnels ability to handle the increase.

Preface

This thesis is my final work in the master's program Applied Data Science at the University of Stavanger.

I want to thank Reggie Davidrajuh and Naeem Khademi for providing me with the problem and setting the scope of work for this thesis.

The work has been extremely intriguing and educational, as well as providing a one-of-a-kind perspective into Petri Net and tunnels. This was an area I had relatively little knowledge of before. The thesis has presented many exciting challenges and through the work I have developed my abilities to implement complex Petri Net and compare the outcome of these based on different parameters.

Joakim Gjermundstad
Stavanger, 15.06.2022

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1. Introduction

In Norway, there have been approximately 1200 road tunnels constructed, which are spread out across the European, national, and county road networks in Norway (Rake & Rød, 2020). They range in both length and incline, as well as in the volume of vehicular and pedestrian traffic. They may pass through fjords or travel through mountains, have one or two runs, and be located either close to or distant from the nearest populated area. The amount of variation is extensive, and the construction of new road tunnels is a never-ending process; as a result, new records are being set, the country's transportation systems and infrastructure are growing more complex, and more people are becoming reliant on driving in tunnels. As a result of this growth, society as a whole and individuals who utilize roads have different expectations about efficiency and accessibility. The combined length of the tunnels is around 800 kilometres, which is equivalent to approximately 1.5 percent of the entire distance travelled by road (Ringen & Sperrevik, 2013). Accidents that occur in tunnels are typically of significant interest to the public. Multiple tunnel accidents have resulted in substantial damage to the tunnel as well as the equipment utilized in the tunnel. As a direct consequence of this damage, the tunnels have been closed for several weeks. Tunnels that are a part of vehicle routes that have few available detour options appear to be more susceptible to closures that last for an extended period of time. Even though the actual risk of traveling in tunnels is lower than the risk of traveling on roads today, many people who utilize roads have the misconception that tunnels are unsafe places to travel (Ringen & Sperrevik, 2013).

The subject of tunnels is extraordinarily complex due to the fact that numerous aspects, including engineering, safety, and maintenance, need to be taken into consideration at every step of development. This indicates that the construction of a tunnel takes place in accordance with a variety of conditions. These dimensions will alter depending on the purpose that is intended for the tunnel, and as a result, it will have a different width, length, difference in traffic, and particular ways to comprehend, as well as distinct engineering challenges at the proposed location of the tunnel.

Due to the fact that a tunnel is a closed structure, there is a more complicated situation regarding the occurrence of accidents. Accidents involving vehicles that occur in tunnels tend to be especially hazardous since there is a greater risk of fire, which makes it more difficult for rescue workers to assist victims in a timely manner. A collision in these systems tends to be quite difficult to predict, and it can become a deadly serious situation in an instant for everyone who is currently inside the system. This is because smoke development can make it difficult for occupants inside tunnels to see and breathe in the event of a potential fire. There are many instances in history that serve as examples to highlight how catastrophic a circumstance like that might be (Amundsen, De fem store tunnelbrannene i Norge, 2017).

As science and technology evolves, new methods are developed to enhance tunnel safety and reduce the overall number of accidents that occur within a tunnel by increasing the number of precautions that are taken there. The European Union (EU) has offered monetary assistance to a number of directives in an effort to improve the level of general safety in tunnels in member countries (Beard & Carvel, 2005). In addition, the European Union has implemented a number of legislation and regulations to oversee the general quality and safety of tunnels on the trans-European road network in order to reduce the apparent risk that comes with driving through tunnels (European Union, 2009). There are a wide variety of collisions that can take place on the road network, and several research have been conducted in an effort to identify the root causes of these collisions and develop preventative measures. The great majority of collisions take place on open stretches of roadway; however, tunnels are also responsible for some of the most serious collisions. When the significant disparity in the total length of the two criteria is taken into consideration, the seriousness of the situation becomes even more apparent (Dysvik, Homleid, & Andreev, 2021).

1.1 Structure and description of thesis

This thesis will be comprised of four primary responsibilities. The first step is to do research into the tunnels and other factors that are relevant to the phenomenon of traffic accidents occurring in tunnels. Find data that will help you understand which parameters are factors in the road structure throughout the country, as well as how these parameters interact with each other, so that you can evaluate any dangers that may arise.

Secondly, following an analysis of the relevant previous research, the data ought to be partitioned into several situations. It is also necessary to determine the primary parameters, which include the kinds of vehicles, the roadway specifications, and the traffic parameters. These examples and parameters will be utilized in a model to determine how they interact with one another as well as which improvements may be made to reduce the likelihood of accidents occurring and the severity of the outcomes that are typically associated with tunnel accidents.

Thirdly, making a mathematical model with modular petri nets is the next step in the process after gathering and organizing all of the information and background studies that are relevant to the problem at hand. This model ought to allow for simple adjustments to be made to the various parameters that are utilized in the simulation, as well as adjustments to the physical structure of the tunnel. This will result in the construction of additional lanes, roundabouts, and possibly other elements inside the tunnel.

Finally, following the construction of the mathematical modular Petri nets, a simulation should be carried out, making use of real-life data obtained from the Norwegian Road Authorities. The information is gathered on a daily basis from a variety of locations all around the Norwegian road network. This data will give the essential real-life information that is required in order to generate simulations that are correct.

2. Theory

2.1 About tunnels

There are numerous countries that are home to a plethora of tunnels, one of which is Norway, which has an extraordinarily high road tunnel distance in comparison to its population. There is a great need for the construction of tunnels since there are many difficulties in the overall terrain. Even though there are always brand-new tunnels being constructed, there is still a significant amount of work to be done in order to bring the previously constructed tunnels up to the new requirements that have been established by the European Union and other regulatory bodies in Norway (European Union, 2009).

There are a few distinct patterns in the data that can be seen in the table that comes from the research on incidents that occurred in Norwegian tunnels. There has been around a 13.2 percent increase in the number of tunnels constructed, and on average, the tunnels are now about 23 percent longer than they were in the past (Amundsen & Ranes, Trafikkulykker i vegtunneler – en analyse av trafikkulykker fra 1992-96 i vegtunneler på riksvegnettet, 1997). There could be a number of reasons for this, including more cost-efficient construction technologies and the fact that expensive low- priority projects eventually get approved as a result of the benefit they provide to society. In either case, the number of tunnels that are being built is always increasing, and each new tunnel features longer and more complex construction. When looking at the building manuals published by the Norwegian Road Authorities, tunnel safety is consequently given a high emphasis.

2.2 The reason for tunnels

Tunnels are necessary for a variety of reasons, particularly with regard to the road system in Norway, and this is especially the case given the current situation. Tunnels are essential to the development of a safe and efficient road network in Norway because the country contains a large number of mountains and fjords. The number of kilometres cut down by the construction of a tunnel results in significant savings in terms of both time and money for people who utilize the road network on a day-to-day basis. In addition, various locations are at an extremely high risk of landslides, avalanches, and rockfalls. The addition of a tunnel would represent a significant improvement in the level of safety along many of these roadways. A tunnel could make an incline or descent considerably more efficient, which is important to keep in mind while thinking about the environment. It is feasible to reach the summit of a mountain by a route that is in a straight line rather than one that is twisted. This will allow the driver to keep a consistent speed throughout the drive. Tunnels are also useful when a fjord needs to be traversed, which is another application for them. In the past, the road network was dependent on ferries. However, in recent decades, subsea tunnels have emerged as a common alternative to eliminate the need for the more time-consuming ferries. The Norwegian Road Authorities have also started looking into an enormous project that will make the entirety of E39 free of ferries by building subsea tunnels and other structures, like the possibility of a floating tunnel (Statens Vegvesen, 2022). It may also be helpful in preventing the construction of highways in nature preserves and the destruction of significant landmarks or structures in certain circumstances. To briefly highlight some of the advantages:

- Cutting the long way by driving straight thorough
- Protection from rockslides and avalanches
- Environmental benefit when maintaining constant speed on mountain passes
- Avoiding the need for ferries
- Conserve nature reserve and important landmarks

2.3 Accidents in tunnels

Tunnel accidents may happen for a number of different causes, and the severity of the accident can vary depending on a number of different factors. Every little thing, from a careless and negligent driver trying to multitask to the absence of regular maintenance on brakes or other essential vehicle elements, can lead to a disastrous outcome. This may be exacerbated by the characteristics of the tunnel, such as its length, the number of vehicles that pass through it on a regular basis, and the possibility of an elevation, as is the case with subsea tunnels. In addition to the maximum allowed speed through the tunnel, another aspect that can play a role in an accident is the kind of vehicle that was involved. Therefore, the person who is ultimately responsible for the construction of a tunnel ought to take into consideration the safety in a variety of different scenarios and formulate policies to minimize and control various risk scenarios, such as a fire or other mishaps. It is possible to take this into consideration by reducing the number of curves and slopes in the tunnels. Lighting that is adequate, a sufficient number of exits designated for emergencies, and fire extinguishing equipment all play a vital role. On roadways with a very high volume of traffic, a cross-section that is broader may provide sufficient room to prevent accidents and may make it simpler to avoid engaging in risky driving while passing large cars on highways with several lanes.

There have been some studies conducted that take a look at the various zones and try to break out where accidents happen and why they do so, in order to acquire a better knowledge of the general incidents that take place in tunnels on the Norwegian road network. There are some significant indicators that there is a higher number of accidents in on the open road system, but the severity is often higher inside tunnels especially in the inner zone, as indicated in Figure 2 in Chapter 2.3.3. However, accidents in the midzone might be more lethal since emergency rescue operations might be more complex in the midzone. The following bullet points provide a summary of some of the study's findings that are particularly interesting to consider.

- Accidents with only one vehicle involved accounted for 52 percent of the total number of collisions that took place.
- Twenty percent of the accidents were caused by vehicles colliding head-on with one another. The majority of these mishaps took place inside tunnels that were, on average, somewhat more constrained in width.
- Rear-end collisions were responsible for 13% of all of the accidents that occurred. According to the findings, the most prevalent contributing cause of those incidents was the high level of traffic.
- The remaining 15% were various accidents that did not fit any of the other criteria, and they were considered miscellaneous (Amundsen & Engebretsen, Studies on Norwegian Road Tunnels 2 - An Analysis on Traffic Accidents in Road Tunnels 2001-2006, 2009).

According to the findings of the study, the number of accidents that occur in tunnels with two lanes is significantly higher. When it comes to the construction of tunnels, there are a number of different considerations that are significant. Because the conduct of the driver may not be foreseeable, it is essential to ensure that the experience is as uncomplicated as is humanly possible. As a result, there is a need for precise standards to be set on the curvature inside the tunnel in order to reduce the amount of cornering that is required while also keeping the driver engaged (Amundsen & Engebretsen, Studies on Norwegian Road Tunnels 2 - An Analysis on Traffic Accidents in Road Tunnels 2001-2006, 2009).

When considering the many construction options for a tunnel, the priority should be placed on ensuring the travellers' safety first and foremost. This is dependent on a variety of circumstances, some of which are listed below (Burns, Beard, & Carvel, 2005):

1. The design of the tunnel
2. The operation of the tunnel
3. Emergency response: actions taken in an emergency

This is of the utmost importance since taking safeguards helps prevent accidents, the likes of which might lead to a potentially lethal scenario in which chemicals or a fire spread through a tunnel (Beard & Carvel, 2005).

People will be able to exit the tunnel in a secure manner in the event that there is an obstruction or during any other emergency situation because the tunnels have been planned in such a layout. The prevention of collisions between vehicles and with infrastructure is one of the most important aspects of road safety. Other aspects of road safety, such as reducing the mechanical impact and the number of casualties, preventing injuries, and lowering the risk of fires, are also vitally important.

There are several types of tunnels built in various environments, but the tunnel's characteristics play an important part in the causes and effects of the accident. Weather conditions, road functionality and condition, tunnel length, and traffic volumes all have a significant impact on the types of tunnel accidents that occur, as well as their placement with regard to the entry, exit, and transition area. In comparison, the summary of road conditions revealed that wet road surfaces result in 38 percent of accidents, while snowy environments result in 35 percent of accidents in the transition area.

The Norwegian Public Roads Administration is extremely worried about the number of accidents and other types of occurrences that take place within the tunnels. When compared to the road network outside, the accident risk on the inside of tunnels is significantly lower. Nevertheless, concerns regarding the lack of safety in tunnels are continuously being voiced in the wake of specific incidents that have taken place within a tunnel.

Accidents that have occurred in Norwegian tunnels, such as the Seljestad incident in the year 2000, the landslide that occurred in the Hanekleiv tunnel in the year 2006, the fire that occurred in the Oslofjord tunnel in the year 2011, and the fire that occurred in the Gudvangatunnel in the year 2013, have received a great deal of attention both in the media and internally in the Norwegian Public Roads Administration. Accidents that occurred in Norwegian and foreign tunnels led to a modification of the legislation, as well as the introduction of new standards for the design, building, maintenance, operation, and management of the tunnels. The modification of the legislation is frequently the result of extensive research into the events in question. Since 2005, the Accident Investigation Board in Norway has been responsible for conducting investigations into various events, including traffic accidents. In the directives given to the Norwegian Public Roads Administration, it is required that the safety suggestions that are included in the reports written by The Accident Investigation Board be implemented.

2.3.1 Accident risk in road tunnels

Tunnels under highways have a lower risk of an accident than comparable portions of roads do now, in part because there are fewer different kinds of accidents that can occur in tunnels than there are on roads today (Amundsen & Engebretsen, Studies on Norwegian Road Tunnels 2 - An Analysis on Traffic Accidents in Road Tunnels 2001-2006, 2009)

The severity of the most prevalent types of road tunnel accidents is significantly higher than that of comparable road accidents that occur today. Today, the probability of a fatal accident occurring in a road tunnel is 53 percent higher than the likelihood of such an accident occurring on roadways (Nitsche & Nussbaumer, 2008). According to the findings of the same research, the likelihood of being involved in an accident in a tunnel is far lower than it is on today's roadways. Between the years 1992 and 1996, rear-end crashes were by far the most prevalent type of accident that occurred in Norwegian tunnels. Tunnels under roads see around twice as many of these kinds of collisions as the rest of the road system combined (Amundsen & Ranes, Trafikkulykker i vegtunneler – en analyse av trafikkulykker fra 1992-96 i vegtunneler på riksvegnettet, 1997). This is especially true for tunnels that are found within cities.

According to the findings of Amundsen and Engebretsen's (2009) study of accidents that occurred in Norwegian road tunnels during the period 2001-2006, the three types of accidents that occur the most frequently in road tunnels are as follows: collisions between vehicles driving in the same direction - rear-end or field change (43%), single accidents (35%), and meeting accidents (15%).

There is a significant disparity between the severity of accidents and the risk of accidents that occur in various areas of road tunnels (Amundsen & Engebretsen, Studies on Norwegian Road Tunnels 2 - An Analysis on Traffic Accidents in Road Tunnels 2001-2006, 2009). When it comes to road tunnels, the likelihood of an accident occurring near the entry zone is often three to four times higher than it is farther within the tunnel, but the severity of the accident is typically highest in the middle zone of the tunnel.

According to studies, the alterations in lighting conditions that occur inside road tunnels induce drivers to reduce their speed (Rinalducci, Hardwick, & Beare, 1979). Amundsen (1994) also found that the average speed of vehicles dropped by 10–20 percent when they approached the entry zone of tunnels. A slowdown of this magnitude can raise the probability of an accident occurring.

According to Sagberg et al. (1999), the most significant behavioural issues that are related with road tunnels include sudden deceleration and changes inside position when driving into road tunnels. This kind of change in behaviour can be caused by a variety of factors, including variations in the light and driving conditions.

According to studies conducted in Norway, accidents that occur in road tunnels frequently involve big trucks. The percentage of incidents that include heavy vehicles is significantly higher in tunnels (22%), which is more than twice as high as what would be expected based on the volume of heavy vehicles and the proportion of accidents that occur on open roads (Amundsen, Vegtunneler – dødsfeller eller trafikksikkerhetstiltak, 1996). Even if the likelihood of severe accidents is lower in tunnels than it is on highways today, Jenssen et al. (2006) point out that the potential for disaster like for an example a fire, is higher in tunnels.

As a result of the three devastating fires that occurred in Central European tunnels between 1999 and 2001 (one each in the Mont Blanc tunnel, the Tauern tunnel, and the St. Gotthard tunnel), there has been a greater emphasis placed on tunnel safety (Stene, Jenssen, Bjørkeli, & Bertelsen, 2003). These occurrences were caused by flames that originated in large vehicles.

2.3.2 Accidents resulting in personal harm and severity of injury

In the period between 2005 and 2012, there were a total of 1057 accidents involving personal injuries that occurred in tunnels that were part of the European, national, and county road networks. When looking at all types of accidents that result in human harm, rear-end collisions are by far the most common sort of accident, as seen in Figure 1. There were 55 people deceased, 89 people critically injured, 904 people injured to a lesser extent, and 9 very seriously injured (Ringen & Sperrevik, 2013). Adding up, 153 people have been fatally injured or died as a result of accidents involving tunnels.

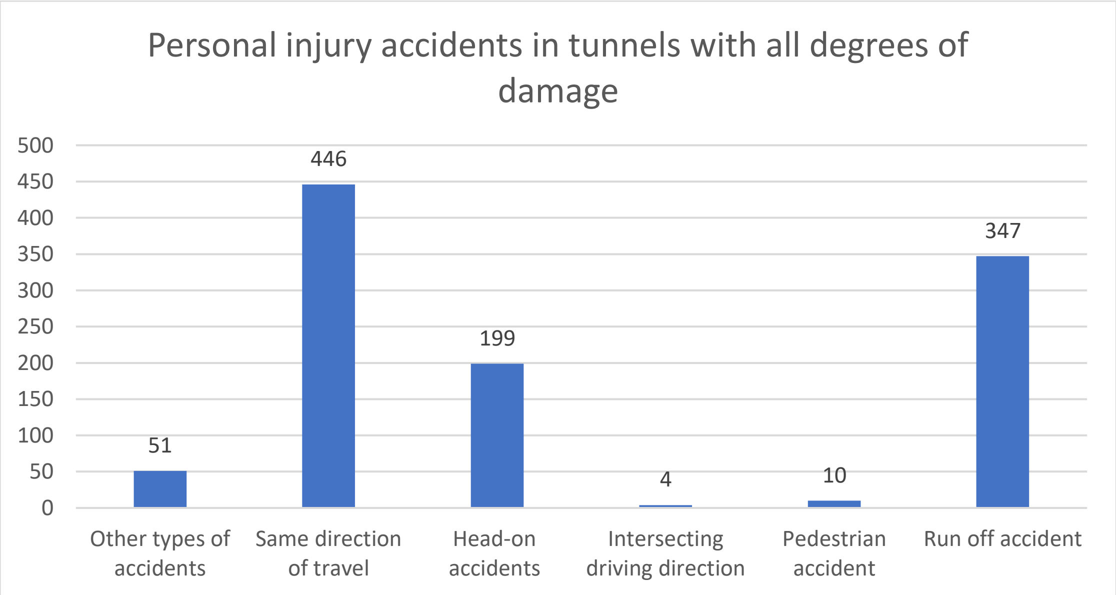

Figure 1: Personal injury accidents in tunnels. All degrees of damage. 2005 - 2012accidents in tunnels (Ringen & Sperrevik, 2013).

2.3.3 Accidents by zone inside tunnels

Previous research (Amundsen & Engebretsen, Studies on Norwegian Road Tunnels 2 - An Analysis on Traffic Accidents in Road Tunnels 2001-2006, 2009) defined zone 1 as the final fifty meters outside of the tunnel, zone 2 as the first fifty meters within the tunnel, zone 3 as the subsequent fifty to one hundred and fifty meters, and zone 4 as the inside of the tunnel.

In the course of this investigation, there have been accidents that have taken place just outside the tunnel. These accidents include situations in which the vehicle that triggered the accident—that is, the vehicle that caused the accident—was either heading away from the tunnel or heading into the tunnel. There has been no attempt to pinpoint an exact distance from the tunnel as a foundation for determining whose accidents are being looked into by the investigation.

In a similar manner, incidents that occur in the entrance zone might be caused by cars either on their way into the tunnel or on their way out of the tunnel. Even in this case, there is insufficient evidence to support the conclusion that the accident took place in the entrance zone because a precise measurement of the distance between the location of the accident and the opening of the tunnel has not been performed (Ringen & Sperrevik, 2013).

The portion of the tunnel that lies within the boundaries of the entrance zone is known as the inner zone. The inner zone is the location of the majority of deadly accidents. The amount of work that needs to be done in each zone's traffic cannot be calculated, although for each tunnel, the length of the inner zone is typically substantially longer than that of the entry zones. Because of this, among other factors, there will typically be a higher number of accidents there compared to in the other zones. A total of 87 people has lost their lives as a result of the 77 tunnel accidents. Figure 2 takes into account the area surrounding the tunnel entrance as well (Ringen & Sperrevik, 2013). When compared to the other zones, the number of people died per accident is significantly higher in the zone that is located outside of the tunnel.

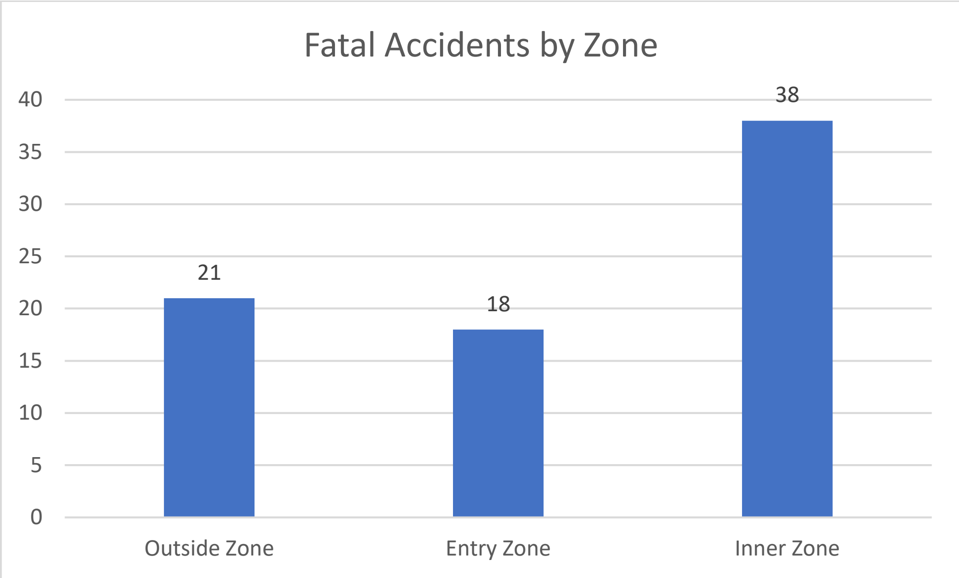

Figure 2: A diagram showing which zone fatal accidents occur (Ringen & Sperrevik, 2013).

Figure 3 illustrates the distribution of the different scenarios that resulted from the accidents mentioned above. From the figures, there is an indication that the most severe incidents happen in the inner zone. This might be correlated with the difficulty to perform emergency rescues in the inner zone.

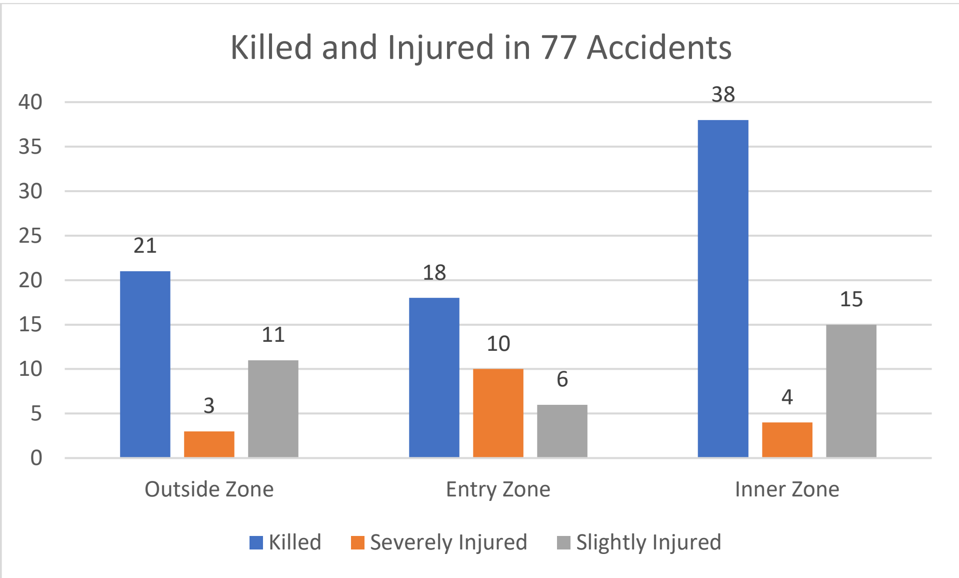

Figure 3: Diagram illustrating the distribution of outcomes in accidents (Ringen & Sperrevik, 2013).

2.3.4 Accidents by type of tunnel

The majority of incidents take place inside of and close to one-lane tunnels, which also account for the majority of the total number of tunnels. This is illustrated in Figure 4. The majority of accidents that take place in tunnels with two lanes occur going downhill. Vehicles traveling downhill have been seen to collide with the edges of emergency exits located within the tunnel as well as masts and posts located outside the tunnel (Ringen & Sperrevik, 2013).

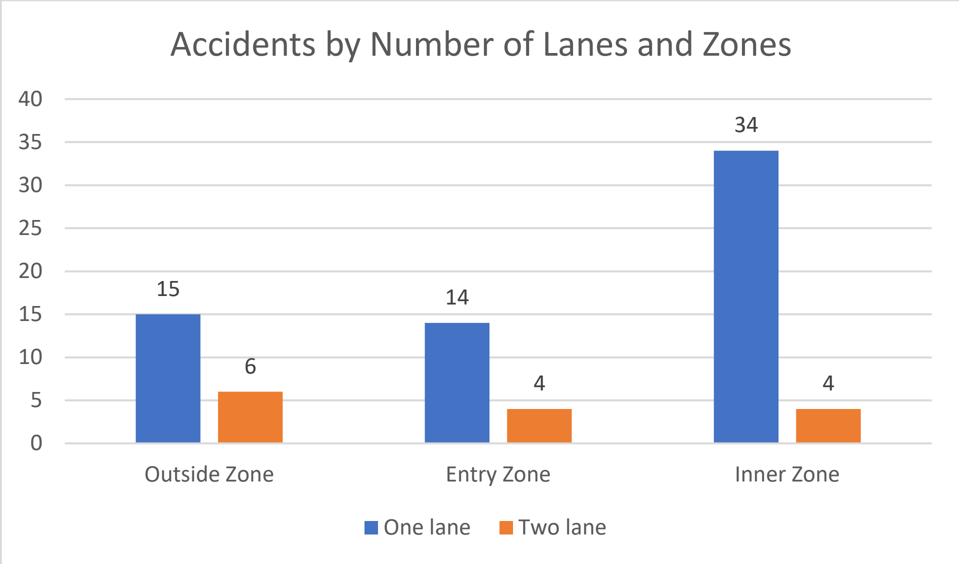

Figure 4: Accidents by Number of Lanes and Zones (Ringen & Sperrevik, 2013).

Most accidents occur in land tunnels as shown in Figure 5. In particular, accidents happen quite frequently in the interior zone of subsea tunnels. Seven out of the 15 fatal accidents that occurred in subsea tunnels occurred on portions where the vehicle that triggered the accident had a length drop that was 8% or steeper (Ringen & Sperrevik, 2013). Six of these collisions were caused by vehicles traveling at speeds that were far higher than the posted limit.

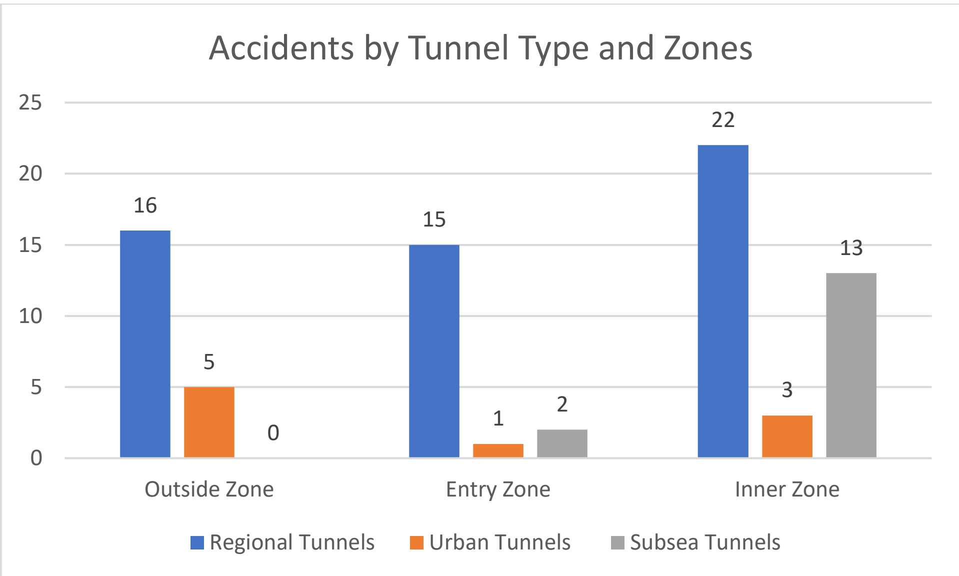

Figure 5: Accidents by tunnel type and zones.

2.3.5 Types of accidents

86% of all fatal incidents in tunnels are meeting accidents and downhill accidents. Accidents that include meetings are the most common form of accident that can occur in the inner zone. The different kinds of accidents have distinct patterns of occurrence in relation to the zones. In the area outside of the tunnels, there are a disproportionately high number of accidents that occur downhill. In the inner zone, head-on accidents dominate shown in Figure 6 (Ringen & Sperrevik, 2013).

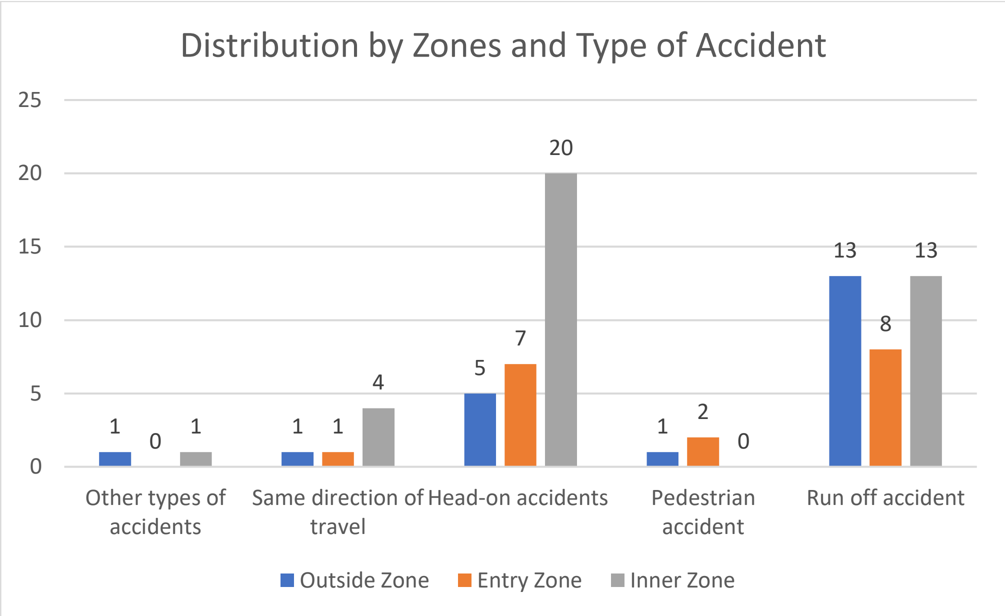

Figure 6: Distribution by zones and type of accident (Ringen & Sperrevik, 2013).

Between the years 2005 and 2012, there were a total of 1057 accidents in tunnels in Norway that resulted in human injuries. During that time period, there were a total of 56 accidents that resulted in fatalities that happened in Norwegian tunnels.

In the tunnels, accidents that occurred in the same direction of travel (rear-end collisions) account for 42 percent of all accidents, but only 9 percent of fatal accidents, as shown in Figure 7. This difference can be seen when one compares the number of fatal accidents to the total number of accidents that resulted in personal injury. The number of people killed in incidents that involve meetings accounts for nearly half (48%) of all fatal accidents. Accidents that take place during meetings cause substantially more extensive damage than accidents that take place during rear-end collisions.

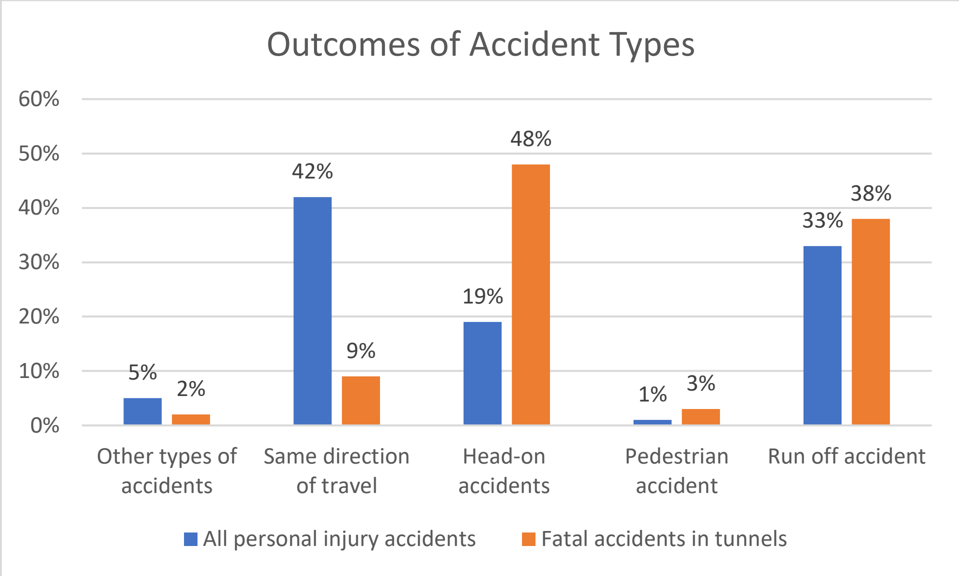

Figure 7: Outcomes of Accident Types measured in precent of total accident (Ringen & Sperrevik, 2013).

2.3.6 Speed Limits and Vehicle Distribution

With a general speed limit of 80 km/h, the majority of accidents take place. After the speed limit was lowered to 70 km/h, there were ten accidents that resulted in fatalities. There have been five slip-and-fall incidents on the downward slope. The fact that people were not wearing seat belts and driving at high speeds contributed to the fact that the incidents were still fatal.

Eighty percent of the vehicles that were involved in the 77 fatal incidents that were investigated for this study were passenger cars and vans, which have a length that is less than 5.6 meters. This percentage also includes motorcycles. Twenty percent of those engaged are large vehicles, which is a higher percentage than the fraction of the road network otherwise occupied by these vehicles. On the other hand, large cars are just a factor in three incidents when it comes to triggering other vehicles (3.8 %). The majority of accidents (79.2%) are caused by passenger vehicles such as cars and vans (Ringen & Sperrevik, 2013).

2.3.7 Psychological effects and driver actions

In addition, the psychological impacts of driving through a tunnel have been the topic of some research in recent years. An overall sense of unease as a result of the presence of uncertainty as well as the claustrophobic experience of driving in a tunnel in contrast to driving on an open road. When entering a tunnel, the sudden transition from light to black can give some drivers a sensation of unease as well as a sense of impending danger (Lee, Kirytopoulos, Pervez, & Huang, 2022). This is one of the contributing factors. When a subsea tunnel is factored into the equation, a vehicle operator may experience increased anxiety due to the sensation of traveling through a pitch-black passageway that is located beneath a body of water. The severity of accidents that take place in tunnels, combined with the overall complexity of these mishaps, has presented the regulating road authorities with a difficult safety engineering dilemma to overcome. Simulations such as this one may be helpful in understanding the general aspects and traffic patterns that occur in a variety of scenarios with a wide array of parameters such as the number of lanes, the type of vehicle, and the varying widths and types of tunnels.

- Tunnels are inherently risky places, and despite the predetermined overall design and the intricate security measures that an entrepreneur may have put in place, there is no assurance that a tunnel will be free from danger. The prevention and control of any potential fires that may break out in tunnels is one of the most crucial issues.
- There are multiple reasons why a fire may occur in a tunnel. It might happen because of an accident or a collision between vehicles. Another possibility is the overheating of an engine or that dangerous and flammable cargo ignites. No tunnel is exempt from the possibility of something happening, and all scenarios must therefore be accounted for to minimize the overall risk.
- A collision on an open road is not the same in terms of severity as one that takes place inside a tunnel. The majority of the time, an accident that occurs in a tunnel is more severe in terms of the amount of damage caused to the road structure, the amount of economic loss, and the number of people injured.
- As long as there is any chance that a collision could cause a vehicle to catch fire, there is no simple answer to this overarching problem. However, there are several steps that can be taken to mitigate this risk.

2.4 Difference between tunnel and open road

When considering the tunnel as a whole, the likelihood of being involved in an accident is typically lower than it is on comparable roads in today's society; however, the likelihood of being involved in an accident that results in significant injury is comparable to or even higher.

Tunnels, on average, have 26 percent fewer personal injury accidents than one road a day when everything else, including the amount of traffic, is the same; however, the number of people killed and seriously injured is about the same as it is on the road today (Høye, Utvikling av ulykkesmodeller for ulykker på riks- og fylkesvegnettet i Norge, 2014). Model calculations using Norwegian accident data show that tunnels, on average, have fewer personal injury accidents than one road a day. Lemke (2000) found that German tunnels with two lanes have an accident risk that is between 35 and 50 percent lower than a comparable road today, and that German tunnels with one lane have an accident risk that is 55 percent lower than a comparable road today. These findings are specific to German tunnels. On the other hand, the differences in the expenses associated with accidents between tunnels and highways in modern times are roughly equivalent. According to the findings of Caliendo et al. (2013), an increase in the amount of traffic in tunnels is related with a greater rise in the number of serious accidents by about 2.1% per percent increase in traffic volume than with a rise in the number of less serious accidents, which will increase by 1.5% per percent increase in traffic volume. According to Caliendo and Guglielmo (2012), two-lane highway tunnels have approximately sixty percent more severe accidents than highways do now on average (Høye & Elvik, Utforming av tunneler, 2016).

Studies that were conducted in Norway and Sweden in the 1990s (Hvoslef, 1991) (Mo, 1980) found that tunnels have an average of 15 percent fewer accidents than roadways do now within 95 percent confidence interval. The difference between tunnels and roads in today's world was most pronounced in places with a high population density; in these locations, tunnels had 61% fewer accidents than roads do in today's world within a 95 percent confidence interval (Høye & Elvik, Utforming av tunneler, 2016).

There are multiple distinctions between tunnels and open road systems, including the following:

- There is very little or no side activity inside a tunnel
- Other conditions during the winter months
- Consistent lighting conditions throughout the day and year, with the exception of the entry zone
- Difficulty judging the incline and decline of the terrain
- Difficulty judging the distance to the next vehicle
- Other concerns relate to safety, emergency services, and so on

This indicates that a few of the design aspects need to be different than what is currently used for the road. In this regard, important aspects include:

- Choosing the appropriate construction and equipment solutions during the design and construction phase with a view to minimizing overall costs over the life of the project
- Obtain a standard that is consistent across all tunnels of the same type and traffic volume when those tunnels are located on the same stretch of road.

3. Classification

The higher the traffic volume and the longer the tunnel, the stricter the requirements for the standards must be. As a result, the tunnels are separated into classes based on their geometric quality and the expected traffic volume. One should keep the length of tunnels for city streets and highways to a maximum of four kilometres, but exceptions are often made when necessary.

When constructing a tunnel's cross-sectional geometry, horizontal and vertical profiles, and access roads, extra care must be given to safety. This is because these factors have a considerable impact on the likelihood of accidents occurring and the severity to which they can lead.

3.1 Choice of tunnel class

When discussing traffic volume, it is common practice to refer to all-year traffic. This is the annual total traffic volume expressed as total traffic in both directions and is calculated by dividing the annual total traffic volume by 365. The classification of the tunnel needs to be decided based on the volume of traffic that is anticipated to use it twenty years after it first opens.

In the event that the volume of traffic fluctuates significantly throughout the day or the year, or if there is a considerable deal of ambiguity in the foundation for the calculation of year-round traffic in 20 years, the classification of the tunnel must be chosen based on a particular evaluation. The Norwegian Public Roads Administration needs to provide its blessing before a different tunnel class can be chosen.

As shown in Figure 8, the tunnels are categorized into several classes according to the total traffic mileage and the length of the tunnel. The tunnel classes serve as the point of departure for selecting the tunnel profile, the number of tunnel runs, the requirements for emergency exits, locations at which the vehicle can be turned, walkable cross connections, emergency exits, and safety equipment. Tunnel profiles are selected according to Figure 8 for tunnels longer than 500 meters. Figure 8 also applies to tunnels that are under 500 meters, but these selections can be modified as long as the shoulder width remains unchanged along the entire tunnel. (Statens Vegvesen, 2006).

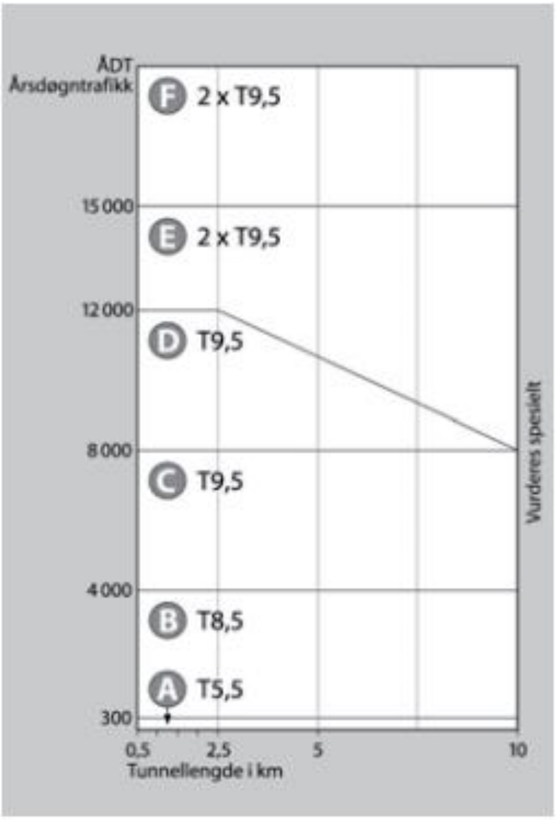

Figure 8: Classification of tunnels based on length(km) and traffic per 24 hours. (Statens Vegvesen, 2006)

Class A tunnels are those that are located beneath single-lane highways with less than 300 vehicles per day of year-round circulation. When designing these kinds of tunnels, use the tunnel profile shown in Figure 10. Tunnels of classes C and D are always constructed using the T9.5 tunnel profile. Each of the runs in a class E or F tunnel has a tunnel profile of T9.5 built into it. Tunnel profiles of T8.5 are used in the construction of class B tunnels. When planning the construction of a secondary tunnel, this factor must be taken into consideration if the traffic level in 20 years will provide the tunnel a class E rating during the period. In the event that the building of tunnel number two must be delayed, preparations must be taken to facilitate the straightforward installation of this tunnel run at a later time. If the average daily traffic flow over the course of a year provides the tunnel a class D rating after 20 years, then it needs to be evaluated in the same manner to determine when the additional safety precautions that come with a class D rating need to be finished. No later than the time when the traffic volume falls within the parameters of the present tunnel class, the measures have to be put into effect (Statens Vegvesen, 2006).

3.2 Tunnel profiles

The overall width at road level determines what the tunnel profiles are called; for an example, see figure 4.2. The tunnel profile T4 has walls that are supposed to be straight. Above the level of the carriageway, the tunnel profiles T5.5 through T12.5 are meant to have a circular profile. With the exception of tunnels designed for pedestrian and bicycle traffic, the minimum free height requirement in tunnels is 4.6 meters. The free height criterion must be met with the structure measured perpendicular to the roadway and with the middle of the line serving as the point of measurement.

An increase in the minimum height requirement has been implemented in the normal profiles in order to guarantee the following:

- Additional clearance for the later adjustment of the road surface
- Normal tolerances for the road superstructure as well as water and frost protection/ casting (combined deviation = 0.1m).
- Both the criteria for free height and the curb height can be satisfied.

In most cases, the profile of the tunnel will make room for signage and other technical installations. Each particular situation is evaluated to see whether or not there is a requirement for local expansions. A minimum height of 4.8 meters above the roadway is required for any technical equipment. A particular clearance from traffic control is required for equipment that is side-mounted, such as road signs. The side-mounted signs ought to be positioned in such a way for the sake of egress that the open height under the sign ought to be a minimum of two meters. Tunnel profiles in tunnels that are longer than 500 meters are required to have lanes that are a minimum of 3.25 meters wide. The minimum width for lanes that are designed for heavy, slow-moving traffic is 3.5 meters. For roadways with narrower lanes, a risk assessment is required to be carried out that documents preserving the same level of security or increasing it through the implementation of alternative security measures (Statens Vegvesen, 2006).

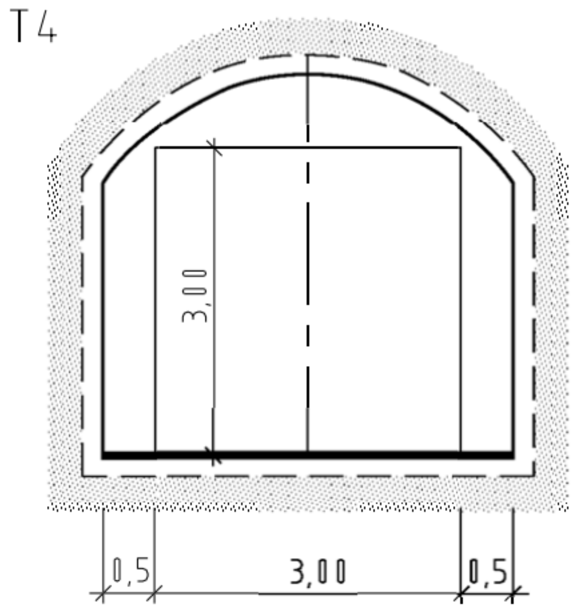

Figure 9: Tunnel profile T4 (Statens Vegvesen, 2006)

Paths for pedestrians and cyclists are marked with the letter T4, shown in Figure 4. The clear height requirement is a minimum of 3.0 meters. T4 is utilized for constructing walkable cross links between tunnels as well as emergency exits from tunnels to the outside air.

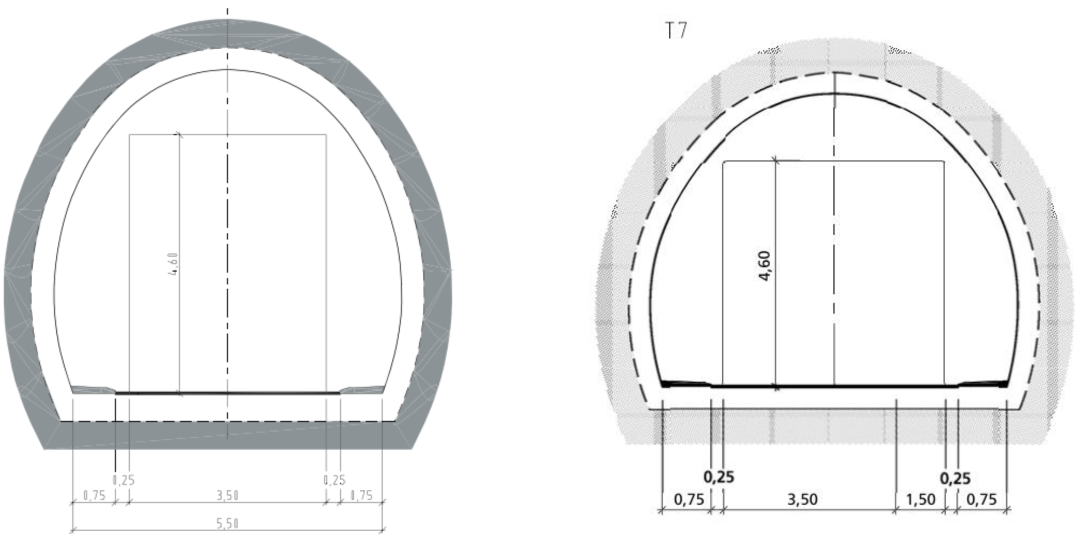

Figure 10: Tunnel profile T 5.5 and T 7 (Statens Vegvesen, 2006)

T5.5 is going to be used for exit and access ramps that only have one lane, and there won't be any requirements that a damaged vehicle has to be able to be driven around. In tunnel class A, the T5.5 designation is utilized for one-lane highways that contain meeting locations. In place of curved walls, straight walls are another option for usage in single-field tunnels. T5.5 is utilized for the construction of escape tunnels.

The T7 is going to be utilized for the exit and access ramps, and it will have one lane that is wide enough for a crashed vehicle to pass through. The road's width of 5.0 meters allows for the safe passing of cars that have come to a complete stop. The driveway has a lane marking of 3.5 meters and an accident field marking of 1.5 meters. In order to satisfy the standards for visibility, the accident field was incorporated into the width extension.

T8.5 shall be used for tunnels in tunnel class B. Tunnels of classes C and D that have two-way traffic are required to employ the T9.5 classification, seen in Figure 11. Both of the tunnels of tunnel class E and tunnel class F are required to use the T9.5.

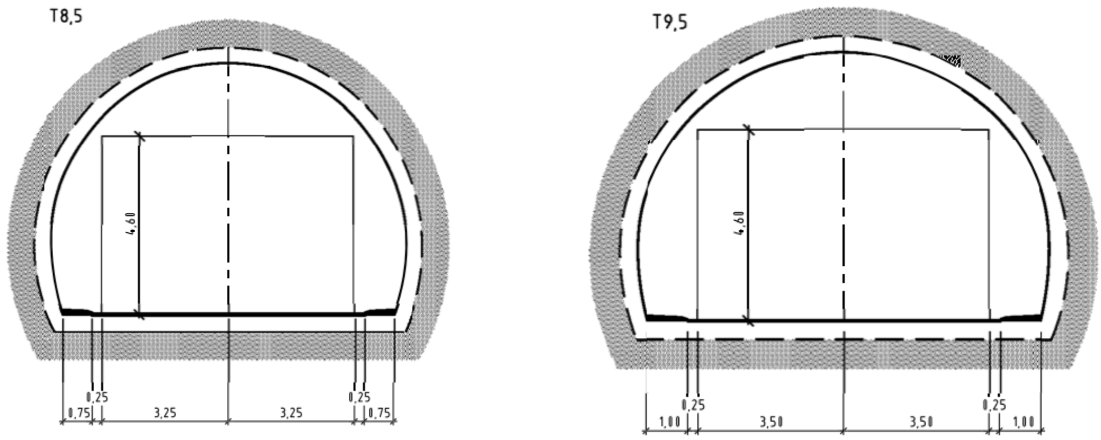

Figure 11: Tunnel profile T8.5 and T9.5 (Statens Vegvesen, 2006)

In tunnels of class B, T11.5 shall be utilized wherever there is a requirement for three lanes or an accident niche (Statens Vegvesen, 2006). Additionally, the design makes room for two lanes in addition to a pedestrian and cycling route that is divided by concrete fences. In other circumstances, the partition of the field needs to be evaluated on the basis of the traffic conditions at the location.

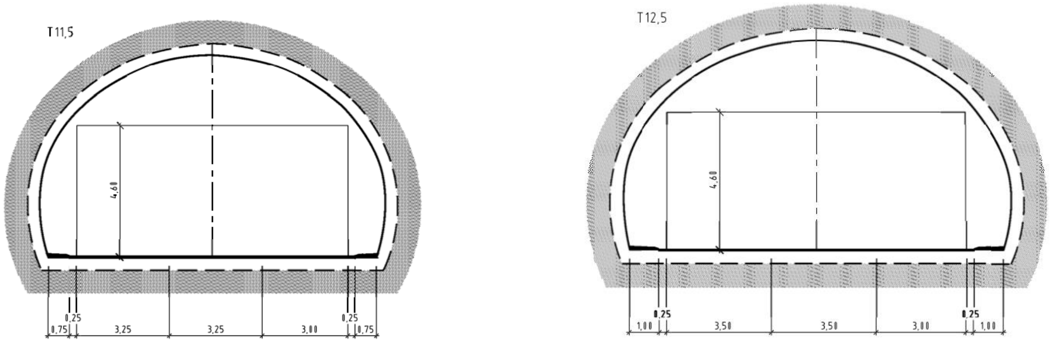

Figure 12: Tunnel profile T 11.5 and T 12.5 (Statens Vegvesen, 2006)

In tunnels of classes E and F, the T12.5 shall be utilized wherever there is a requirement for three lanes or an accident niche. The diagram depicts the regular field division at the time the accident started. In other circumstances, the field division needs to be evaluated according to the existing traffic conditions on-site.

Table 1 showing some of the requirements for each of the different classifications of a tunnel. Here some specifications from the total width and width of each driving lane are particularly important.

Table 1: Geometric dimensions for the various tunnel profiles (Statens Vegvesen, 2006)

Profile	Total Width	Width of driving laine	Wall Radius	Centre Hight Wall Radius	Heng Radius
T4	4.0	3.0	-	-	2.40
T5.5	5.5	3.5	4.79	1.77	2.59
T7	7.0	5.0	4.79	1.57	3.20
T8.5	8.5	6.5	4.79	1.77	4.50
T9.5	9.5	7.0	4.79	1.57	5.20
T11.5	11.5	9.5	4.79	1.77	7.20
T12.5	12.5	10.0	4.79	1.57	7.45

3.3 Alignment inside tunnels

As a result of the unique conditions that exist within tunnels, the standards for alignment in tunnels differ from those on the road. Both the interior and exterior of the tunnel are required to retain the same number of lanes. Any alteration in the number of lanes must take place an adequate distance before the entrance to the tunnel. This distance must at least be equal to the distance that a vehicle travels in ten seconds when traveling at the highest speed permitted (Statens Vegvesen, 2006). In the event that this cannot be accomplished, it will be necessary to either take additional precautions or strengthen existing ones.

3.4 Dimensioning speed inside tunnels

The level of visibility in the tunnel serves as the primary factor in determining the size of the smallest horizontal curve. Because of driving dynamics, the curves can therefore be trafficked at a faster pace than the dimensioning would indicate, as shown in Table 1. If the tunnel is more than 2.5 km long, the design speed should be set to at least 80 km/h (Statens Vegvesen, 2006). If the tunnel's slope is greater than or equal to 5% for at least one kilometre, the dimensioning speed must be set to at least 80 km/h. For tunnels that are shorter or that are in urban areas, the dimensioning speed is adapted to the portion of road that the tunnel merges into.

Table 2: Requirements for stop sight in meters for different degrees of inclination, year-round traffic and dimensioning speed (Statens Vegvesen, 2006).

Speed limit km/t	Traffic in 20 years 0-1500			Traffic in 20 years 1500-4000			Traffic in 20 years >4000		
	-8% ≤	-7 - +7%	≤ +8%	-8% ≤	-7 - +7%	≤ +8%	-8% ≤	-7 - +7%	≤ +8%
50	55m	49m	41m	59m	57m	47m	64m	54m	49m
60	72m	64m	58m	79m	68m	61m	88m	73m	64m
70	94m	82m	74m	109m	87m	77m	116m	94m	82m
80	119m	102m	91m	131m	109m	96m	149m	119m	102m
90	146m	124m	110m	164m	134m	116m	189m	147m	124m
100	178m	149m	131m	201m	162m	139m	234m	178m	149m
110	215m	177m	154m	244m	193m	165m	288m	215m	177m
120	255m	208m	180m	293m	229m	193m	350m	255m	208m

3.5 Curvature and visibility

At both ends of the tunnel, there should be some thought given to laying onto a curve, in order to prevent vehicles from passing one another and to stop daylight from entering the opening and impairing drivers' ability to see the traffic edges. In very lengthy tunnels, more than 6 km, gentle turns are installed to break up the monotony. The horizontal curvature is continuously adjusted to be at the 2/3 stop sight position both inside and outside the tunnel entrance (Statens Vegvesen, 2006). It is of the utmost importance to stay away from the transition between the curved line and the straight line right outside the entrance to the tunnel.

Unless there is no alternative solution that is geographically conceivable, there should not be an incline of more than 5 percent in any new tunnels that are built. Particularly for underwater tunnels, there have been several exemptions made. In tunnels with a slope of more than 3 percent, it is recommended that additional and/or reinforced safety measures be adopted in accordance with a risk assessment in order to increase tunnel safety (Statens Vegvesen, 2006).

3.6 Intersection in Tunnels

It is imperative that tunnel crossings be avoided at all costs, and any exceptions to this rule must be cleared with the Norwegian Public Roads Administration at an early point in the design process. In the event that traversing the tunnel is required to arrive at a suitable solution, it is imperative that certain general criteria be adhered to. Rock-mechanical evaluations have to be carried out first in order to determine whether or not it is necessary to execute width extensions before permission can be obtained to create an intersection within the tunnel. No portion of the road junction inside a tunnel is allowed to be located any closer to the tunnel opening than a length that corresponds to the lighting requirements of the entrance zone and the transition zone. This rule is in place for lighting technical reasons. However, if the deceleration field begins at least 100 meters before the tunnel opens, an exit ramp can be removed from the transition zones. It is required that there be an average brightness level of at least 3 cd/m2 in the region surrounding the intersection as well as on sections that have a lot of lane change in connection with intersections (Statens Vegvesen, 2006).

The intricate layout of the tunnel's crossings makes the ventilation conditions difficult. Therefore, it is essential to take into consideration the technical requirements of the flow and the ventilation system at an early stage in the planning process. In order to prevent accidents, tunnel crossings need to be designed to accommodate greater amounts of traffic than those seen at comparable crossroads on the surface. In the most heavily loaded hour, the dimensioning traffic-to-calculated capacity ratio (v/k) must not go above 0.75. Tunnels are not permitted to make use of X-junctions or other signal-regulated junctions (Statens Vegvesen, 2006).

3.7 Roundabout in tunnels

It is possible to install roundabouts in tunnels that are located in metropolitan areas if the speed level in the tunnel does not exceed 60 kilometres per hour. It is possible to employ either a smaller roundabout with three arms or a larger one with three or four arms and a constructed island in the centre seen in Figure 13.

Mini roundabouts are most useful on local roads that have year-round traffic and are expected to have up to about 5,000 vehicles per day in 20 years. A 3-armed mini-roundabout needs an angle of 120 degrees between the road arms and a defined central island with a diameter of 1.5 meters in order to function properly. Under these circumstances, the clear view zone, which is 10 meters wide and 50 meters long, will correspond with the width extension that moves toward the intersection (Statens Vegvesen, 2006). It is possible to create medium and big roundabouts with pillars of rock or concrete in the central island of the roundabout.

The rock's mechanical properties will determine the size of the pillar that forms. It is important that there be a clear view area that is approximately four meters wide all the way around the pillar. The driving space in the roundabout ought to have a width of between 8 and 10 meters. The diameter of a three-armed roundabout that has an angle of around 120 degrees between the arms can have a modest reduction made to it. (Statens Vegvesen, 2006).

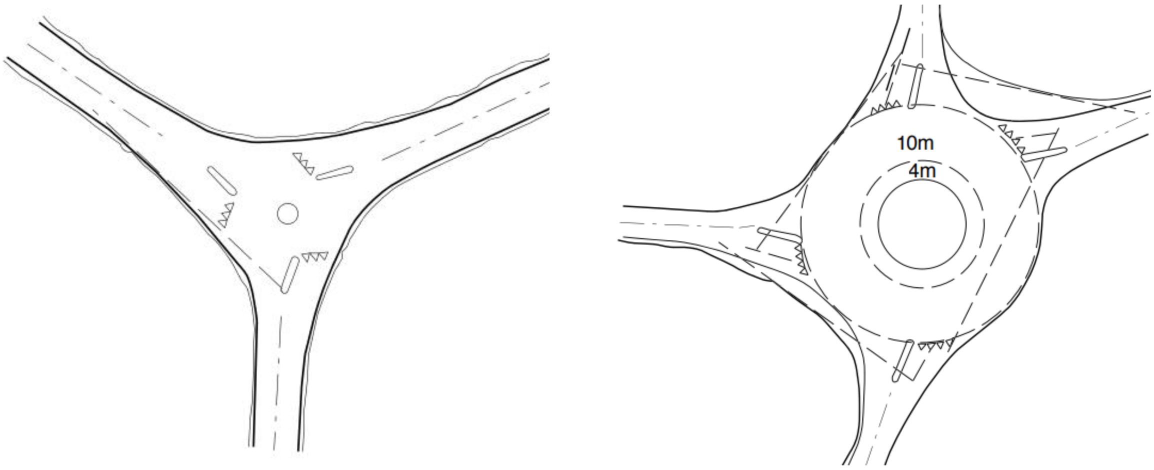

Figure 13: Different types of roundabouts in a tunnel (Statens Vegvesen, 2006)

3.8 Classification of tunnels

There have been significant advancements made in the fields of technology and safe-working environment, including the establishment of national design criteria for road tunnels in several different nations. Consequently, those who are responsible for the planning, construction and operation of road tunnels are now in a better position to evaluate the role of classification methods as a basis for justifying standards of tunnel operation and maintenance. This is because of the positive effects of the situation (Amundsen & Sølvik, Classification of Tunnels, Existing Guidllines and Experiences, Recommendations, 1995).

The Public Roads Administration issued the Norwegian Design Guide titled "Road Tunnels" in the year 1990. This guide contains the criteria that are required for tunnel equipment in Norway. According to their length and capacity, the tunnels that are part of the public road network are separated into one of five different tunnel classes. The tunnel class will determine the profile of the tunnel as well as the necessary equipment. Because the majority of tunnels in Norway have very modest traffic volumes, typically less than 3,000 vehicles per day, it is required to make cost savings in both the tunnel profile and the equipment (Amundsen & Sølvik, Classification of Tunnels, Existing Guidllines and Experiences, Recommendations, 1995). The categorization system is utilized most frequently for newly constructed tunnels; however, it will also be utilized for the retrofitting of safety features into older tunnels in the near future. Figure 8: Classification of tunnels based on length(km) and traffic per 24 hours.

represent a compromise between the quality of the flow of traffic, a high safety standard, and economic considerations. As indicated in the accompanying graphic, the classification of the tunnel is determined by the length of the tunnel as well as the volume of traffic.

In addition, there could be made an argument in this thesis that this is just a classification based on traffic volume and length. As mentioned in Chapter 2 there are other aspects to a tunnel like the possibility to have a roundabout. When looking at tunnel accidents the data is often categorized in reginal tunnels, urban tunnels, and subsea tunnels. Combining this with the classification system used by the Norwegian Road Authorities, an illustrative classification model can be created as shown in Figure 14.

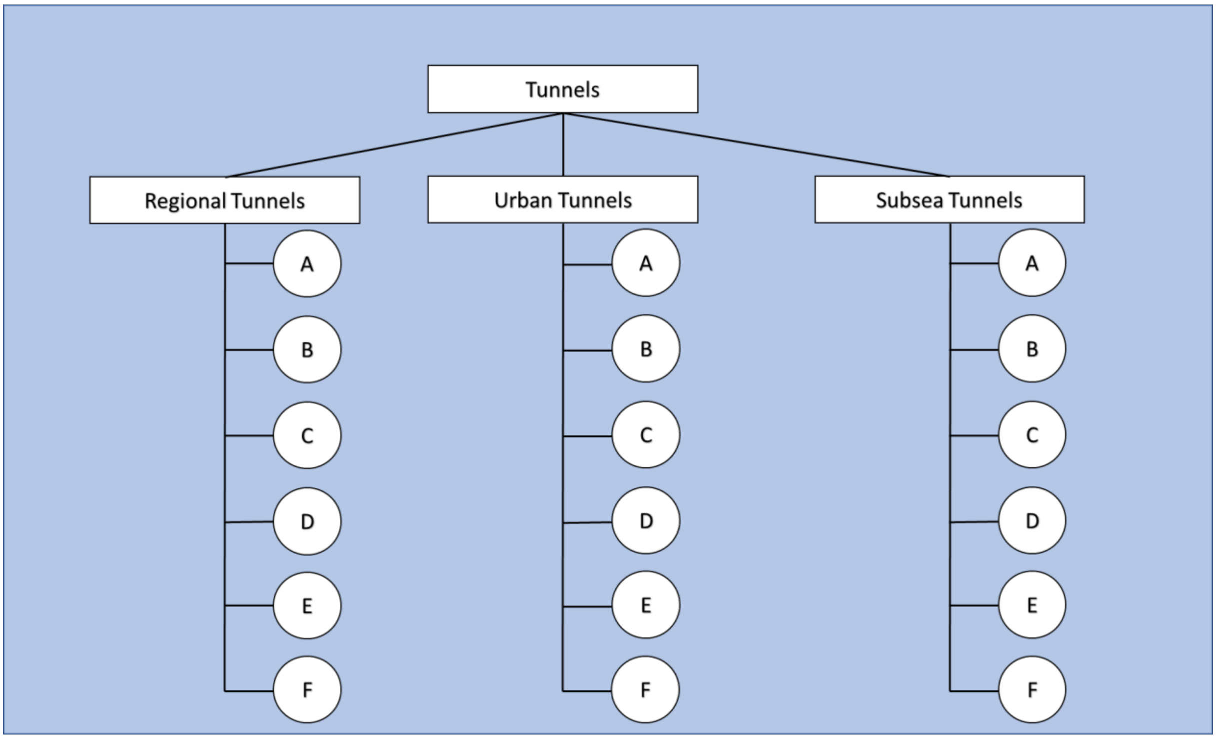

Figure 14: Classification system for tunnels.

4. Method

The method chapter describes how we have proceeded to obtain the knowledge and data that we needed to solve the problem and produce the findings that are presented in this thesis. The report provides an explanation of the reasoning behind the selected methodology and the format of the survey. Before we eventually analyse the validity and dependability of the empirical data, we will first present a step-by-step description of the study method. It is essential to be aware that there is no perfect research procedure because every method will involve probable flaws, limitations, and shortcomings. This is why it is necessary to be aware of this fact. As a result, it is essential to identify and expose any potential flaws that may be associated with the process and the findings (Jacobsen, 2005).

4.1 Inductive, deductive, and abductive data collection

The process of collecting data can be thought of as having three distinct approaches: deductive, inductive, and abductive. When collecting data deductively, one moves from theory to data based on experience or observation. This indicates that one already has a preconceived notion of the outcome, and the data is gathered with the purpose of determining whether or not it supports the theory. When collecting data using inductive methods, one moves in the other direction, from empirical to theoretical. In this section, all of the pertinent information is gathered, and it is then systematized (Jacobsen, 2005).

4.2 Qualitative or quantitative method

One way provides some insight into the manner in which we ought to proceed to acquire or evaluate knowledge. It is usual practice to differentiate between two approaches to data collection: the qualitative approach and the quantitative approach. The qualitative technique collects information that is not capable of being quantified or measured, whereas the quantitative method gives information in the form of quantifiable units. This is the primary distinction between the two methodologies. (Dalland, 2013).

According to Jacobsen (2005), the two methods are equal ways of collecting empirical data, but the choice depends on which problem and research design is chosen. In order to respond to the research assignment and making a simulation, it is important to identify the underlying factors that may affect the outcome of the simulations. It was therefore a natural choice to use a quantitative approach because the method uses measurable data that is necessary in a simulation. A qualitative method collects a lot of information about a few survey units to go in depth, a quantitative method gathers information from a wide perspective by obtaining a small amount of information about many survey units. Data collected quantitatively are linked to separate phenomena. While the qualitative method goes in depth on the topic, looks at the context and the overall picture (Dalland, 2013). When doing an analysis, it is important to discuss the data's reliability and validity, which is done in Chapter 4.6.

4.3 Primary and secondary data

Primary and secondary data are both categories that can be applied to the information that was obtained. Data that is gathered directly from the source is referred to as primary data. Secondary data, on the other hand, refers to data that was collected by third parties for reasons unrelated to our current issue (Jacobsen, 2005). Secondary data has been gathered for the purpose of this thesis. The secondary data mostly consists of documents obtained from the Norwegian Public Roads Administration. These documents include handbooks, accident reports, and statistics collected from actual traffic. Because a significant portion of the material that we acquired in order to find a solution to the problem is subjective, we have verified it with reputable sources. Due to the fact that the credibility of the sources would have a significant bearing on the reliability of the data, an analysis of the sources and the information obtained from them has been carried out. Textbooks, government road reports, and legislation have all been utilized during the process of putting together the theoretical foundation. The regulations of the European Union and other international studies are also used as secondary sources of information. The secondary sources that we have utilized are thought to be reputable and were written by individuals who have experience with the topic in question.

4.4 Petri Nets

Petri Nets are an instrument that was utilized in the completion of this thesis. It's a network that's flexible and easy to use, and it helps explain, model, and simulate complicated systems using data in real time, so that you can acquire a better knowledge of the problem or the system as a whole. As an illustration of this, consider the baggage claim areas at airports and warehouses, as well as the passageways that cars utilize in tunnels.

The proposed model is simple to understand for its users because it does not require much mathematics and has a straightforward user interface. The report offered a GPenSIM model as well as a brief analysis of tunnels, the various characteristics associated with vehicle traffic through them, and the hazards that could be obtained using it.

4.5 The research process

Figure 15 presents an illustration of the study procedure that we have been following. The method began with the gathering of information regarding the assignment in its entirety as the first phase. A basic strategy was established as a result of doing this, as a lot of reports from different entities provided a lot of information that was beneficial. The scope of the thesis was defined by taking into account both the extensive literature review that was done and the question that was given in the assignment.

The next thing that needed to be done in the process was to make a decision on which simulations should be run in order to achieve a good representation of the entire real-time data that was gathered. It was decided to use the General Purpose Petri Net Simulator (Davidrajuh, 2014) in order to mimic the flow of traffic. Within the MATLAB computer programming environment, this is a tool for the modelling and simulation of discrete-event systems (MATLAB, 2021). Following the completion of the simulations, we deliberated on the best approach for data collection. The Norwegian Public Road Authorities release traffic volume information gathered from a variety of data-points located along the Norwegian road network. This can be utilized to determine the volume of traffic that a possible tunnel experiences during a certain time period. Using that as a foundation, there will be the opportunity to adjust some parameters and observe the model's response to the changes.

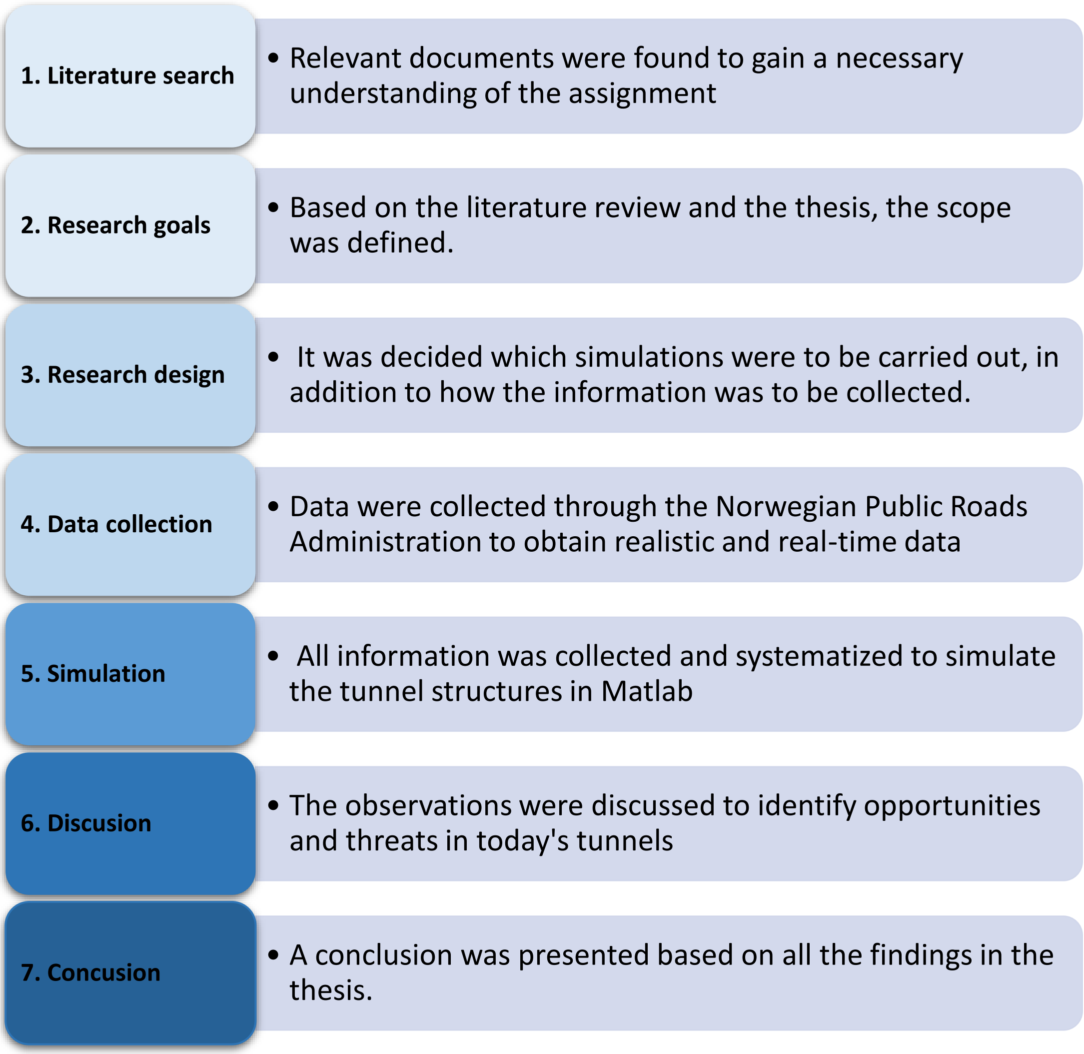

Figure 15: The research process

4.6 Reliability and validity

It is essential to have a conversation about the empirical evidence and the validity of the empirical data in order to determine the degree to which the findings from the analyses are attributable to the methodology or whether or not there is a genuine perception of "reality." The requirements that the empirical data collected should fulfil are as follows (Dalland, 2013):

1. It has to be true and have some bearing on the topic.
2. It must be reliable and trustworthy

The fact that the data has to be legitimate is a guarantee that the information gathered is pertinent to the issue at hand and the questions posed by the research. Because the data has to be trustworthy, the findings of the research have to be trustworthy as well (Jacobsen, 2005). The purpose of this thesis is to do research on tunnels and run traffic simulations under a variety of conditions. Because the data that was collected shows that there are a variety of solutions and constructions for tunnels, the simulation needs to be able to handle variations in the constructions, and one could argue that the data has a great deal of significance to the problem that is being discussed.

Evaluating the dependability of qualitative research, which is the approach that was taken in the development of this thesis, might be a challenging task. The reason for this is that the researcher will have an effect on the gathering of the data as well as the implementation of the analysis. This is due to the fact that the data will depend on the abilities and reasoning of the researcher. Because there is only one author, there are few opportunities for collaboration with other people. Because of this, there is a possibility that the information gained may be misinterpreted, or that a flaw in the simulations may not have been discovered because the work was done by just one person. When possible, it is best to share the findings with a colleague, since this can potentially increase the dependability.

There is a possibility that the information is influenced by bias due to the fact that the primary source was the Norwegian Public Roads Administration. By this, it is meant that the Norwegian Public Roads Administration may have a predisposition view, which may lead to the information they present not being objective. This possibility exists due to the possibility that the Norwegian Public Roads Administration may have a bias. The majority of the material that was acquired is regarded as having good credibility thanks to the utilization of various sources coming from separate organizations. A significant portion of the information originates from first-hand sources, which includes organizations and authors who have a direct link to the subjects being studied.

4.7 Criticism of method

As was previously mentioned, there are no perfect research methods; as a result, there is a possibility that the research method has some deficiencies. The fact that the simulation relies solely on information provided by the Norwegian Road Authorities is a significant limitation. Because the author does not have any local knowledge on some of the simulations, there is a possibility that the models do not replicate the actual scenario. Moreover, the author does not have any local knowledge on some of the simulations. It is possible that there is an error in the dataset, or it is possible that the local users of the tunnels make use of some irregularities when driving in the area that the author is unable to be aware of without being present on site as an observer.

5. Results

5.1 Implementation of Model

This thesis is comprised of a number of different files. To begin, there is the main component of the simulation's files. The simulation is executed using these files on each of the unique systems that were created. In this specific instance, the Petri Net Definition, which is abbreviated as PDF, is contained within a separate file on every occasion. If a system needs multiple PDF files, a separate file is made for each of the system parts, and then a connection file is made to ensure that a unified transaction can take place between the various modules that make up the overall system. In addition, there is a COMMON PRE file and a COMMON POST file for each simulation. These files check to see that the system is in the appropriate state before and after each iteration of the loop. All of this contributes to the creation of a simulation in which there are opportunities to alter parameters and add additional definition files in order to make the simulation more complex. In the most complicated models, it is necessary to create a separate file for some transitions in order to have an overall clear overview of the simulation of the entire system. This is done so that the model can be understood in its entirety.

To begin a simple illustration of making a Petri Net Definition file is shown in the Figure 17 below alongside a Figure 16 that shows the “places” and “transactions” the code creates. Combining the Petri Net Definition files one can make a complete structure and remove parts if it’s not needed. This is a straightforward file in which the structure of the Petri net model was constructed. The places and transitions in the model were given names, and we specified which transitions and places would be connected to one another.

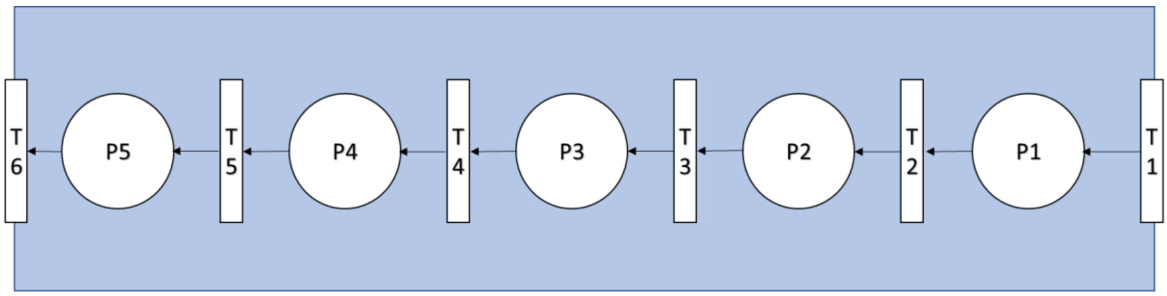

Figure 16: Illustration of a simple model of a tunnel.

In this code the T1 corresponds to “tL1EnterTunnel” and T6 corresponds to “tL1ExitTunnel”. In addition, there are two additional “places” in the code. This is the “pL1Buffer” and “pL1Exit”. The buffer is used to hold all tokens in the beginning of the simulation, and the exit hold the tokens when they passed through and is useful to control that all tokens has exited the tunnel simulation.

```
% PDF - PETRI NET DEFINITION FILE
% Simple Tunnel

function [png] = tunnel_pdf()

png.PN_name = 'General tunnnel structure';


png.set_of_Ps = {'pL1Buffer','pL1Place1', 'pL1Place2', 'pL1Place3',...
    'pL1Place4', 'pL1Place5','pL1Exit'};

png.set_of_Ts = {'tL1EnterTunnel', 'tL1ExitTunnel',...
    'tL1ToPlace2', 'tL1ToPlace3', 'tL1ToPlace4', 'tL1ToPlace5'};


png.set_of_As = {'pL1Buffer','tL1EnterTunnel',1,...
    'tL1EnterTunnel','pL1Place1',1,...
    'pL1Place1', 'tL1ToPlace2', 1,...
    'tL1ToPlace2', 'pL1Place2', 1,...
    'pL1Place2', 'tL1ToPlace3', 1,...
    'tL1ToPlace3', 'pL1Place3', 1,...
    'pL1Place3', 'tL1ToPlace4', 1,...
    'tL1ToPlace4', 'pL1Place4', 1,...
    'pL1Place4', 'tL1ToPlace5', 1,...
    'tL1ToPlace5', 'pL1Place5', 1,...
    'pL1Place5', 'tL1ExitTunnel', 1,...
    'tL1ExitTunnel','pL1Exit',1,...
    };

png.set_of_Is = {'pL1Place1', 'tL1EnterTunnel', 1,...
    'pL1Place2', 'tL1ToPlace2', 1,...
    'pL1Place3', 'tL1ToPlace3', 1,...
    'pL1Place4', 'tL1ToPlace4', 1,...
    'pL1Place5', 'tL1ToPlace5', 1,...
    };
```

Figure 17: Petri Net Definition code to set up the structure in Figure 16.

A basic setup of a tunnel that has only one lane. This is used to see if a simulation is done as intended and that all vehicles pass through the simulation. This can be set together with more complex models, as the Petri Net can be added to other structures and then help to simulate a tunnel with more complex structures as multiple lanes and with roundabouts inside.

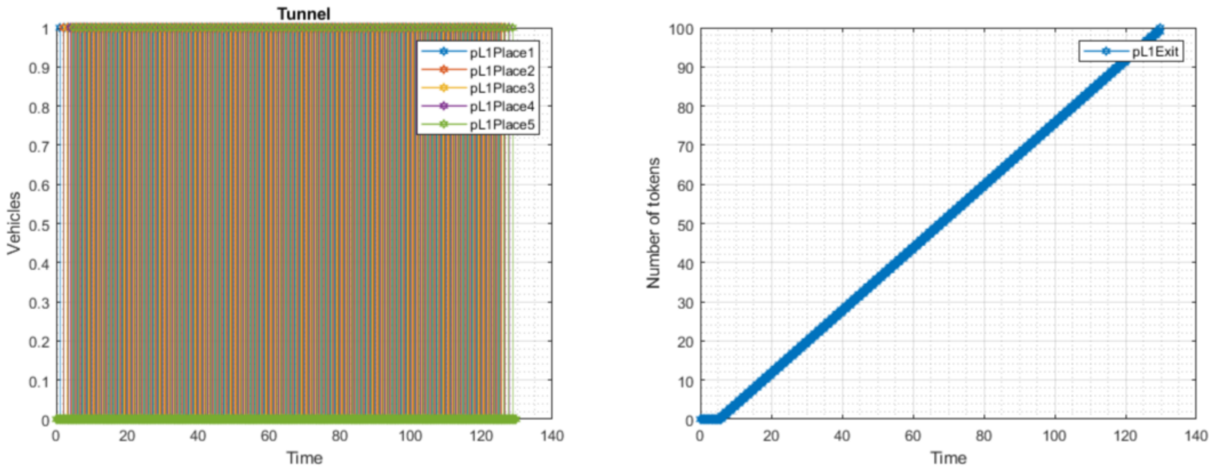

Figure 18: Output from Simple Tunnel simulation.

The output from the simple model, shown in Figure 18, shows that the vehicles pass trough the Petri Net as expected. In this simulation all 100 vehicles goes through, and no “places” has more than one token at a given time during the simulation. This is important as vehicles cannot double stack in a single lane tunnel.

5.2 Modelling a subsea tunnel

Due to the fact that a subsea tunnel typically has two ascending lanes from the bottom, this provides an additional layer of complexity to the overall model. On the way up the incline to the surface, this is a requirement that must be met in order to make it possible for vehicles to pass each other.

It is necessary to find a solution to a problem in order to successfully create two lanes out of one. To begin, a simulation was developed using a simple model that contained a single lane of traffic. After that, there was a division into two distinct lanes. A single semaphore was implemented to ensure that each token only goes to one location after the transition. This was done to prevent the tokens from multiplying as a result of the transition by sending them to both "places."

The Figure 19 depicts a subsea tunnel that begins with only one lane, continues with only one lane until it reaches the bottom, and then splits the lanes. This is done because heavy traffic typically has trouble maintaining the speed limit because the ascent frequently has a higher incline than what is typically allowed inside a tunnel (Gamlem & Høyberg, 2016). Constructors in Norway can apply for special permission from the Norwegian Road Authorities in order to deviate from the standard incline and decline requirements. This is because subsea tunnels are notoriously difficult to build without superseding the allowed inclination. Additionally, some tunnels were built before the requirements that the European standard established for what is required today. This indicates that the incline is steeper than the standards allow, and as a result, it may be tough to operate for certain vehicles.

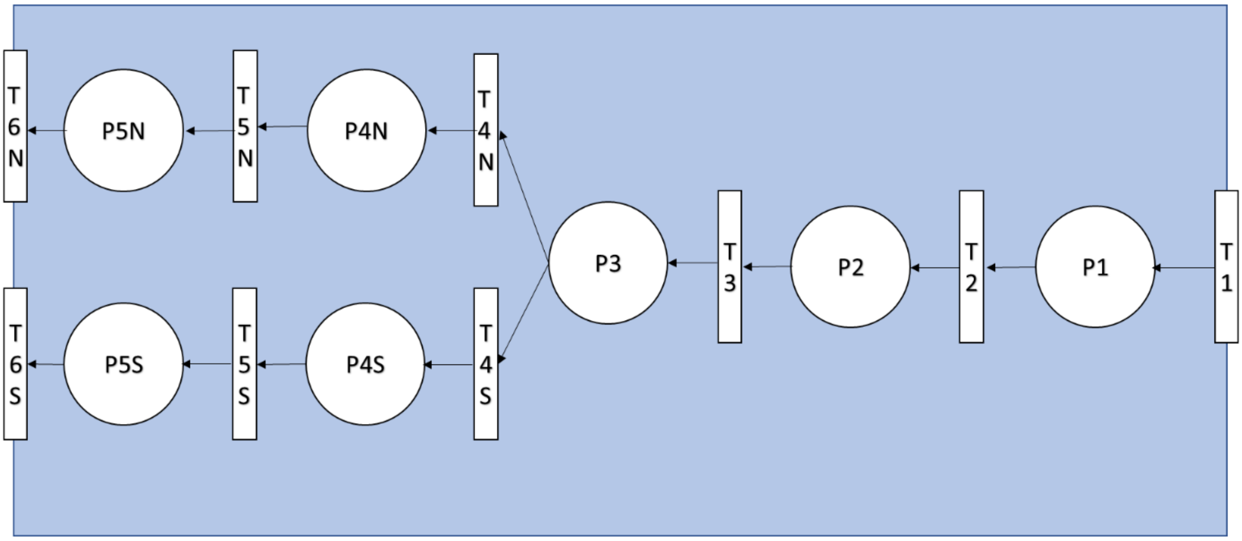

Figure 19: Subsea tunnel with splitting lanes as ascending to the surface.

In the output there we can see that there are multiple exits of the tunnel. When plotting number of vehicles inside the tunnel there are also the possibility to have two vehicles beside one another. As the second lane is used to pass slower moving vehicles, the transitions fire more rapidly in this lane. This is also the reason for the different number of vehicles exiting in the second lane.

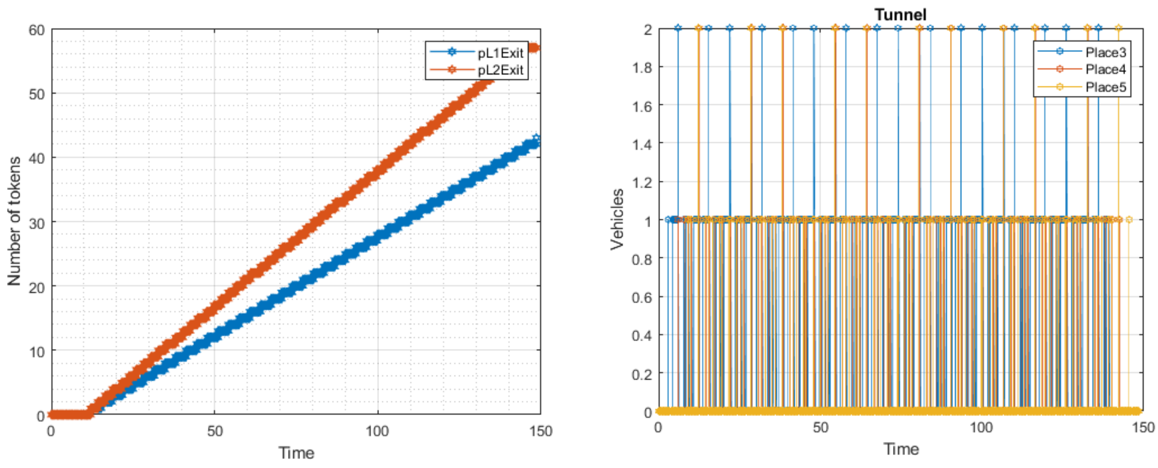

Figure 20: Output from the test running of the subsea tunnel simulation.

5.3 Tunnel with a roundabout inside

It was covered in the theory chapter that it is possible to build roundabouts inside of tunnels if there is a reason for doing so. It is a good solution to avoid additional excavations to add multiple on and off ramps to mimic the same effect as a roundabout. This can be done as a result of the fact that regular cross-intersects are not permitted. A section cut out of Vallaviktunellen is shown in Figure. This section contains a roundabout with three arms. It is possible to simulate the traffic inside because the Norwegian Road Authorities have provided some data points that show the volume of traffic approaching from all sides of the arms. The location of these data points can be seen below.

Figure 21: Illustration of the datapoints in Vallaviktunellen (Statens Vegvesen, 2022).

A simplified model of a roundabout is presented in the Figure 22 that can be found below. It shows the general layout of the structure. In this case, there are three arms just like the one in Vallaviktunellen; however, it is simple to change it so that it functions as a roundabout with four arms by adding a new Petri Net Definition and some additional connections that allow it to work with the overall model. The obvious issue that arises when converting the roundabout is the increased number of "places" that exist within the roundabout as a result of the addition of an entry part.

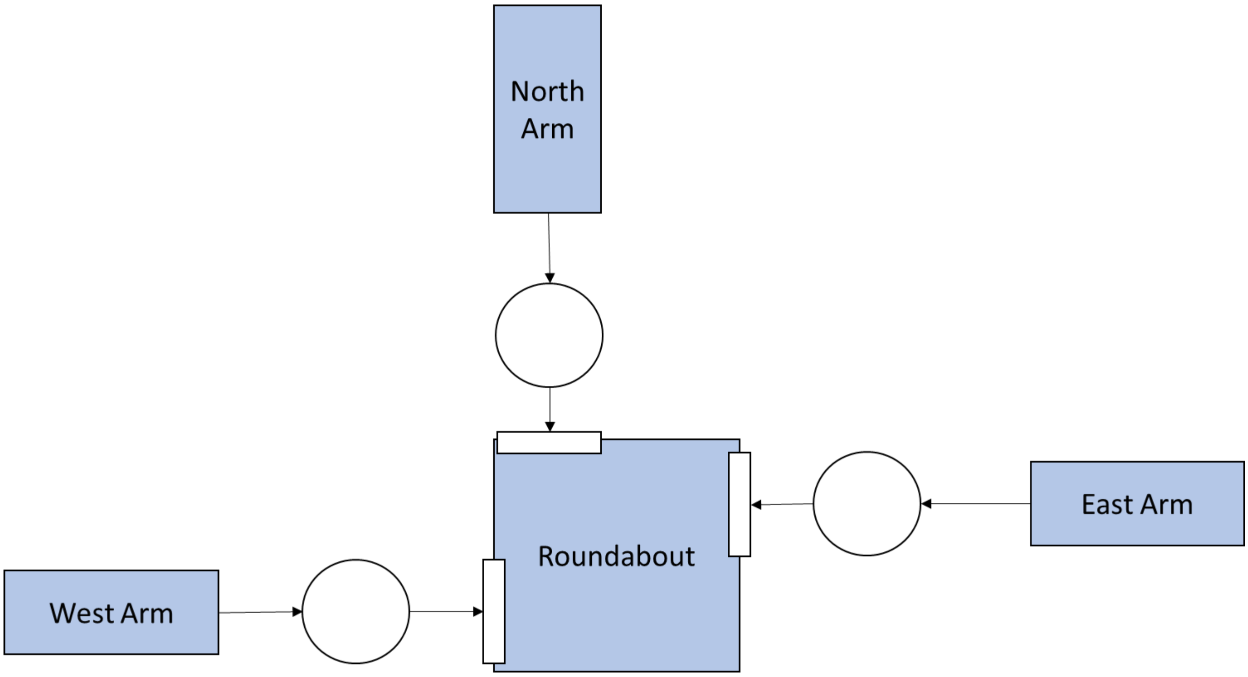

Figure 22: Overview of how a simple three arm roundabout would look.

Figure 22 provides a summary of the model that is presented here. We can see all of the entrances that lead into the roundabout as well as all of the exits that head away from the roundabout. As can be seen in the model, we made use of various locations in order to connect the various modules to one another. The primary concept behind this is that there will be a consistent pace of token generation over the entirety of the simulation. The vehicles will each have a tag indicating the way they should exit in as well as the estimated amount of time it will take them to travel through the roundabout. The exits will direct vehicles leaving in their direction and heading out of the tunnel. This ensures that they don't stay in the roundabout longer than they should. At last, all vehicles will exit and be found in the location that responds to their exit.

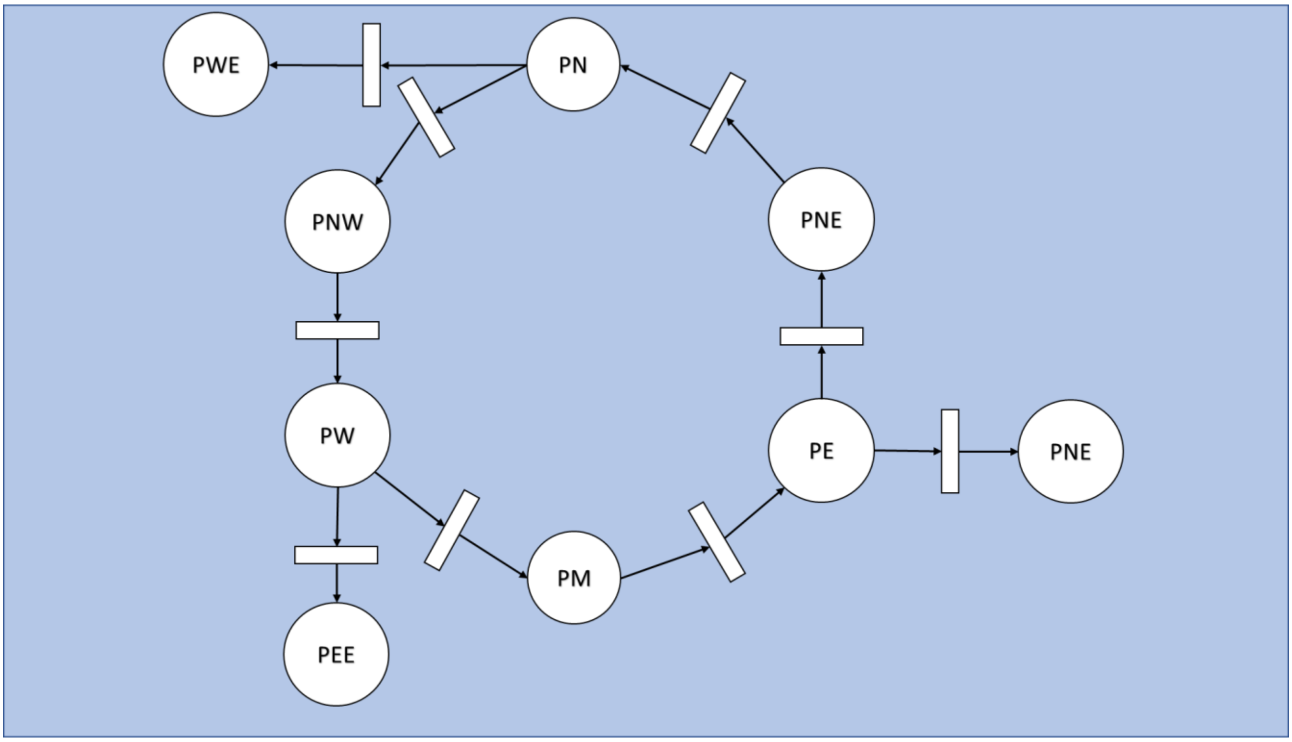

Figure 23: Illustration of the places inside the roundabout in this model.

The model of the roundabout can be shown in Figure 23. There are arcs going into the roundabout from all feasible entries, as well as out of the roundabout to all possible exits. Inhibitor arcs are used (even doe they don't show in the figure) at all entry points to limit the number of vehicles that can enter the junction.

The arc weights of all the inhibitor arcs are three, although there can be more than two cars in the roundabout at the same time. This is because the simulation utilizes an 'ExitRounabout' transition to take a token out of the roundabout.

Tokens are tagged with its journey time in the pre-file for all 'EnterRoundabout' transitions (time to get through the roundabout based on where it is coming from and where it is going). Only the ones that should exit in that direction (based on the colour we labelled it with in the 'EnterQueue' transition in the junction arms) are removed from the 'ExitRoundabout' transitions.

The vehicles are parked inside the actual roundabout model for the duration of their journey (time to get to their exit point). Vehicles generally arrive at a given location at a completely random time. They may arrive alone or in quantity, but not in a linear order. As a result, the entering arms employ a randomized function to provide them with more erratic and genuine arrival rate.

Inhibitor arcs are used combined with and a function to see if the closest transitions (to the left) are firing. This is done to simulate vehicles approaching from the left blocking a car as it approaches the roundabout because of the duty to give way.

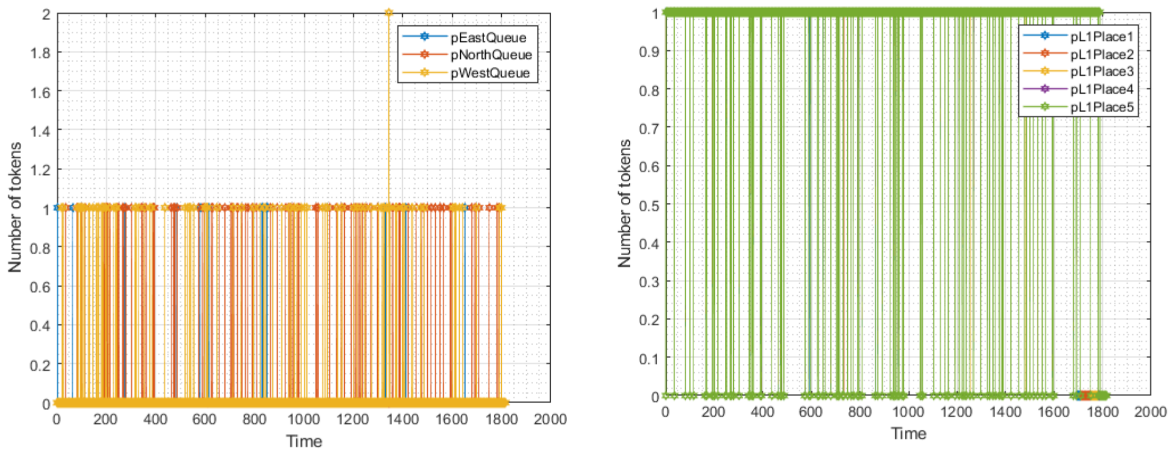

Figure 24: Plots from the simulations with a roundabout in the tunnel using real life data.

Figure 24 shows some plots from the simulation from the tunnel with the roundabout inside. Here data from the Norwegian Road Authorities are used to see of the model can simulate a realistic scenario. The plot to the left shows if any queues are developing in the simulation, and the one to the right shows that there is no place in the tunnel that there are multiple cars in the same "place". As the model to the left shows there are not really any queues forming accept at one point two vehicles are waiting to enter the model. This shows that the model is performing as expected and that the tunnel manages to deal with the traffic volume during peak hours.

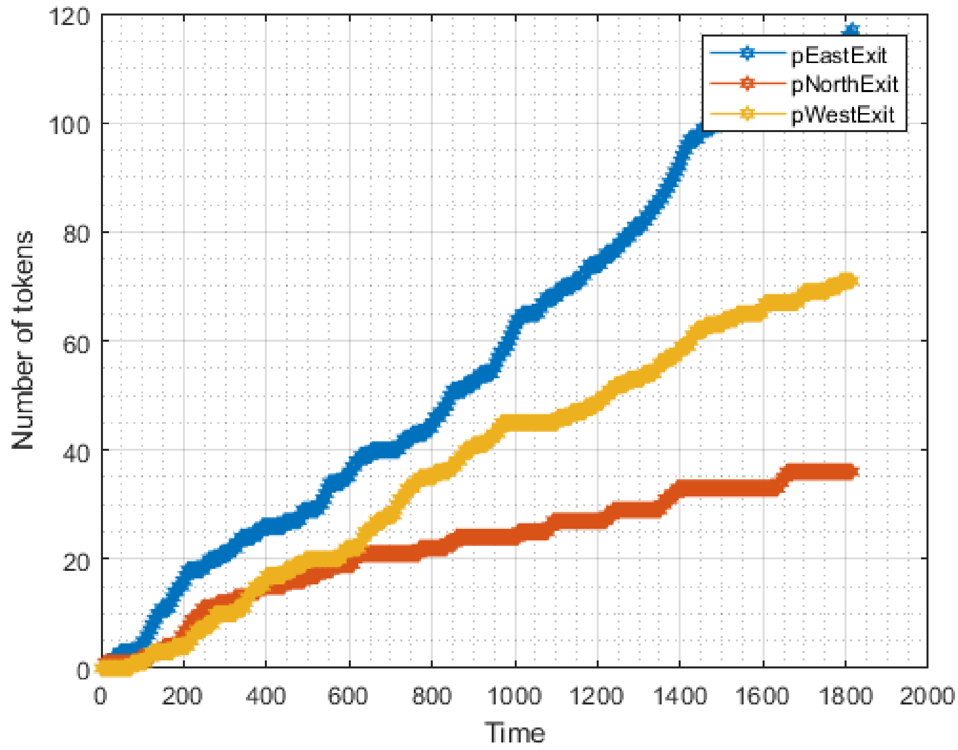

Figure 25: Shows how many cars exits in which direction.

The plot in Figure 25 illustrates the traffic flow to each direction inside the tunnel. As the data from each of the different data points where varying by quite a large margin, there are an uneven distribution of the number of vehicles that exits at each location. As the model captures this it looks like its working as intended.

When looking at the theory there are some regulations to how much traffic a tunnel should be able to handle when being constructed. This is based on the expected traffic volume 20 years into the future from estimated time of compilation. Because of this it is possible to see how the model handles an increase in the traffic volume. By doubling the number of vehicles at each of the data point it should be possible to see how the model handles the increase in traffic.

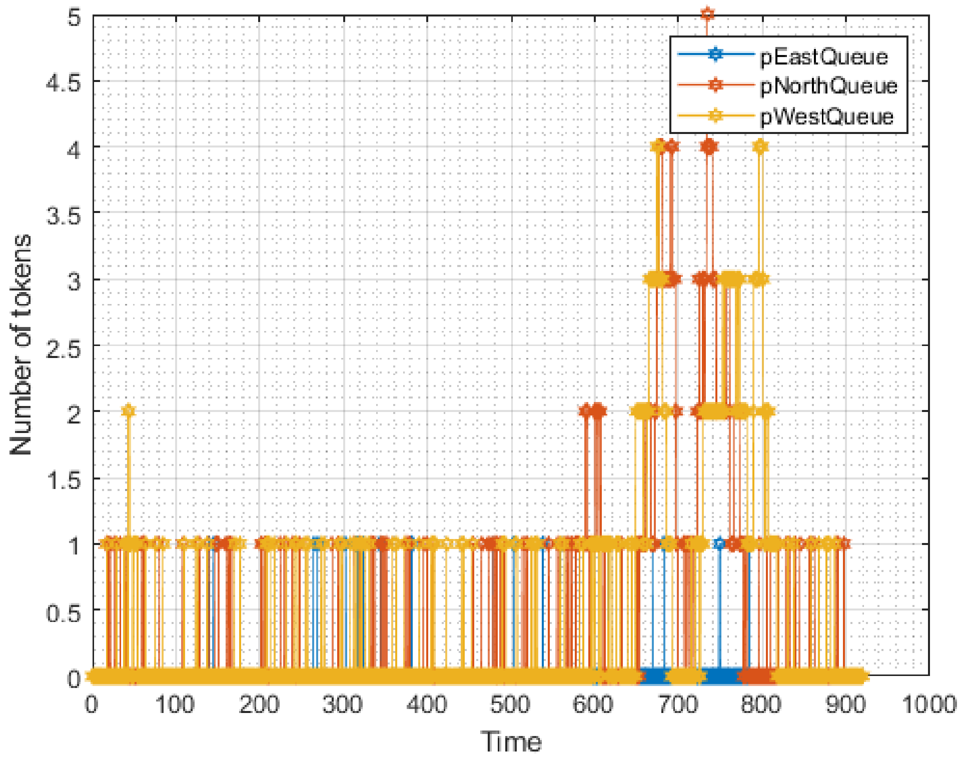

Figure 26: Plot of queues forming when doubling the traffic volume.

As Figure 26 shows, there are clear queues forming when the traffic volume is increased. The time of the simulation is not the same as in previous simulation (15 minutes vs 30 minutes) but this has been accounted for by changing the number of vehicles to make the ratio even. This can be seen in Figure 27 as the number of vehicles is close to equal, but the time interval has changed. The model does not manage to ensure that all vehicles make it through the tunnel without stranding in line at some point during peak hours. As the increase in the number of vehicles was quite large, there is really no surprise that queues are forming. This increase is most likely way larger than the predicted volume in the next then years as the roundabout construction in this tunnel was finished in 2013. Nevertheless, it is clear that the tunnel cannot handle a doubling of vehicles without generating queues. If this scenario where to happen in the next following years, modifications to the tunnel might be necessary since generating a queue inside a tunnel is generally not the best scenario. Even dough roundabouts inside tunnels needs to be close to some of the exits, accidents can become quite serious and should be avoided if possible.

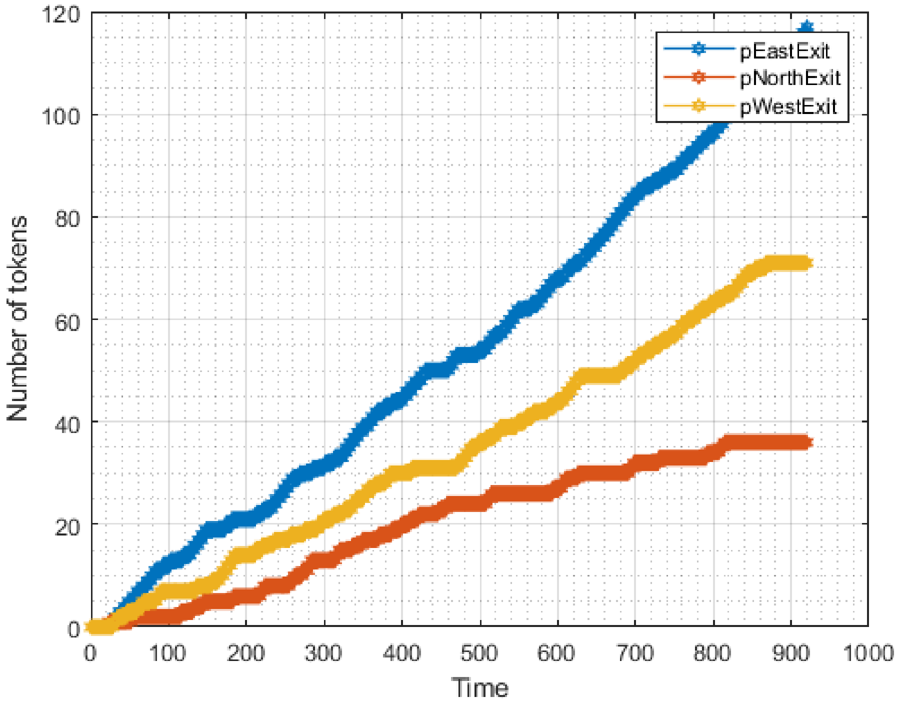

Figure 27: Plot showing distribution vehicles at exits with double amount of traffic.

6. Conclusion

The purpose of the thesis was to do a literary study on tunnels and classify them into some general groups. Part of the literary study was also to look at the accidents happening in tunnels to get an overview of the complete picture and challenges in making tunnels on the road network safer.

Then some Petri Net models where developed based on some of the research from the literary study and classification of tunnels. The Petri Nets that this thesis makes simulations on a basic tunnel to get an overview of the general traffic flow, and how the “places” and “transitions” work within the structure. Then the simulations gradually become more complex when simulating a subsea tunnel with dual ascending lanes and a tunnel based in Vallaviktunellen which has a 3-armed roundabout inside. Data from the Norwegian Road Authorities and used in the simulation to get a real-life simulation. The results of the simulation was as expected with the tunnel and roundabout being able to handle the traffic volume as it is today at peak hours.

Using the knowledge from the requirements from traffic volume from the literature study, there were some possibilities to add additional traffic to see of the model of the tunnel could handle the additional volume without generating large queues. When doubling the traffic volume at peak hours the model still performed fine, but some queues where generated. This was as expecting when doubling the volume as that is quite drastic, but there were quite low effects as the queues quickly decreased and the traffic flow returned to normal.

The models shows that it can simulate the tunnel with the traffic volume as it is today, and then can easily change some parameters to see how the simulated model handles an increase in vehicles. This shows that it can be used as a tool to see how well a tunnel perform with future traffic volume, as this is one of the requirements to get the correct tunnel class during development and construction. A simulation tool loke this may help to ensure that the correct specifications are selected and help avoid future accidents inside tunnels.

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Appendix

Here all code and other files related to the thesis are attached.

Main simulation simple tunnel model

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Main simulation file with simple tunnel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all; clc;
global global_info;
% global_info.DELTA_TIME = 0.1;

%%%%
% How many vehicles expected at each lokation,
% can ude fictional and real numbers from data source
%%%%
% Expected cars to location
global_info.VEHICLES_ENTRANCE = 100;
global_info.TUNNEL_USERS = 0;
global_info.STOP_AT = 100000000;

pns = pnstruct({'tunnel_pdf'
    });

%%%%
% Setting number of vehicles that at each enterance
% in the tunnel.
%%%%
dynamic.m0 = {'pL1Buffer', global_info.VEHICLES_ENTRANCE};
dynamic.ft = {'tL1EnterTunnel', 1, 'tL1ToPlace2', 1, 'tL1ToPlace3', 1,...
    'tL1ToPlace4', 1, 'tL1ToPlace5', 1, 'tL1ExitTunnel', 1};


pni = initialdynamics(pns, dynamic);
results = gpensim(pni);


%%%%
% Select what "Place" to be plotted
%%%%
figure;
plotp(results, {
    'pL1Place1','pL1Place2','pL1Place3','pL1Place4','pL1Place5',...
    %'pNW','pSW','pSE', 'pNE'
    });
%text(global_info.STOP_AT, get_place('pL1Exit').tokens,'  Exit')

xlabel('Time')
ylabel('Vehicles')
title('Tunnel')

%%%%
% Plotting number of cars at the exit
%%%%
figure;
plotp(results, {
```

```
    'pL1Exit',...
    });
```

COMMON_POST

```
OMMOfunction [] = COMMON_POST(transition)

global global_info

if(contains(transition.name, 'Exit'))
    global_info.TUNNEL_USERS = global_info.TUNNEL_USERS + 1;
    if ge(global_info.TUNNEL_USERS, global_info.VEHICLES_ENTRANCE)
        % stop the simulation, because all vehicles
        % has reached their destination.
        disp('STOP SIMULATION, ALL VEHICLES HAS PASED THROUGH');
        global_info.STOP_SIMULATION = 1;
        return
    end

end
```

The Petri Net definition file for this can be found in Figure 17 in the thesis.

Main subsea tunnel simulation.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Main simulation file of subsea tunnel
% with split lanes on ascending and one lane
% when decending
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all; clc;
global global_info;

%%%%
% How many vehicles expected at each lokation,
% can ude fictional and real numbers from data source
%%%%
global_info.VEHICLES_ENTRANCE = 40;
global_info.SEMAFOR=1;
global_info.TUNNEL_USERS = 0;
global_info.STOP_AT = 100000000;

pns = pnstruct({'tunnel_pdf'
    });

%%%%
% Setting number of vehicles that at each enterance
% in the tunnel.
%%%%
dynamic.m0 = {'pL1Buffer', global_info.VEHICLES_ENTRANCE};
```

```
dynamic.ft = {'tL1EnterTunnel', 1, 'tL1ToPlace2', 1, 'tL1ToPlace3', 1, 'tL1ToPlace4', 3,
'tL1ToPlace5', 3, 'tL1ExitTunnel', 3,...
    'tL2ToPlace3', 1.5, 'tL2ToPlace4', 2, 'tL2ToPlace5', 2, 'tL2ExitTunnel', 2};

pni = initialdynamics(pns, dynamic);
results = gpensim(pni);

%%%%
% Select what "Place" to be plotted
%%%%
figure;
plotp(results, {
    'pL1Exit','pL2Exit'...

    });
%%%%%
% Plotting the two lanes to see how many vehicles are in the
% tunnel and at the same distance in the tunnel
%%%%%
figure;
SumandPlot({'pL1Place3','pL2Place3'})
hold on;
SumandPlot({'pL1Place4','pL2Place4'})
hold on;
SumandPlot({'pL1Place5','pL2Place5'})
hold on;
legend('Place3','Place4','Place5');
%sumAndPlotMultiplePlaces({'pL1Exit','pL2Exit'})

xlabel('Time')
ylabel('Vehicles')
title('Tunnel')
```

Petri Net Definition file from the subsea tunnel.

```
% PDF - PETRI NET DEFINITION FILE
% Subsea Tunnel with splitting lines on the bottom

function [png] = tunnel_pdf()

png.PN_name = 'General Subsea Tunnnel Structure';


png.set_of_Ps = {'pL1Buffer','pL1Place1', 'pL1Place2', 'pL1Place3', 'pL1Place4',
'pL1Place5','pL1Exit',...
    'pL2Place3', 'pL2Place4', 'pL2Place5','pL2Exit'};

png.set_of_Ts = {'tL1EnterTunnel', 'tL1ExitTunnel','tL2ExitTunnel',...
    'tL1ToPlace2', 'tL1ToPlace3', 'tL1ToPlace4', 'tL1ToPlace5',...
    'tL2ToPlace3', 'tL2ToPlace4', 'tL2ToPlace5'};


png.set_of_As = {'pL1Buffer','tL1EnterTunnel',1,...
    'tL1EnterTunnel','pL1Place1',1,...
    'pL1Place1', 'tL1ToPlace2', 1,...
```

```
    'tL1ToPlace2', 'pL1Place2', 1,...
    'pL1Place2', 'tL1ToPlace3', 1,...
    'tL1ToPlace3', 'pL1Place3', 1,...
    'pL1Place3', 'tL1ToPlace4', 1,...
    'tL1ToPlace4', 'pL1Place4', 1,...
    'pL1Place4', 'tL1ToPlace5', 1,...
    'tL1ToPlace5', 'pL1Place5', 1,...
    'pL1Place5', 'tL1ExitTunnel', 1,...
    'tL1ExitTunnel','pL1Exit',1,...
    'pL1Place2', 'tL2ToPlace3', 1,...
    'tL2ToPlace3', 'pL2Place3', 1,...
    'pL2Place3', 'tL2ToPlace4', 1,...
    'tL2ToPlace4', 'pL2Place4', 1,...
    'pL2Place4', 'tL2ToPlace5', 1,...
    'tL2ToPlace5', 'pL2Place5', 1,...
    'pL2Place5', 'tL2ExitTunnel', 1,...
    'tL2ExitTunnel','pL2Exit',1,...
    };

png.set_of_Is = {'pL1Place1', 'tL1EnterTunnel', 1,...
    'pL1Place2', 'tL1ToPlace2', 1,...
    'pL1Place3', 'tL1ToPlace3', 1,...
    'pL1Place4', 'tL1ToPlace4', 1,...
    'pL1Place5', 'tL1ToPlace5', 1,...
    'pL2Place3', 'tL2ToPlace3', 1,...
    'pL2Place4', 'tL2ToPlace4', 1,...
    'pL2Place5', 'tL2ToPlace5', 1,...
    };
```

COMMON_POST

```
function [] = COMMON_POST(transition)

global global_info

disp(['transition "', transition.name, ...
 '" completed firing at ', rt_clock_string(), '!']);

if strcmp(transition.name, 'tL1ToPlace3'),
    global_info.SEMAFOR = 1; % tL1ToPlace3 releases semafor to pL1Place3
else strcmp(transition.name, 'tL2ToPlace3'),
    global_info.SEMAFOR = 1; % tL2ToPlace3 releases semafor to pL2Place3
end


if(contains(transition.name, 'Exit'))
    global_info.TUNNEL_USERS = global_info.TUNNEL_USERS + 1;
    if ge(global_info.TUNNEL_USERS, global_info.VEHICLES_ENTRANCE)
        % stop the simulation, because all cars has reached their
        % destination.
        disp('STOP SIMULATION, ALL VEHICLES HAS PASED THROUGH');
        global_info.STOP_SIMULATION = 1;
        return
    end
```

```
end
```

COMMON_PRE

```
function [fire, trans] = COMMON_PRE(trans)
global global_info;
p2 = get_place('pL1Place2');
if (strcmp(trans.name, 'tL1ToPlace2')|| strcmp(trans.name, 'tL2ToPlace2'))
    if (eq(p2.tokens,0) && eq(global_info.SEMAFOR, 1))
        global_info.SEMAFOR=0;
        fire=1;
    else
        fire=0;
    end
else
    fire=1;
end
```

Simulation based on Vallalviktunnelen. This tunnel has a 3-armed roundabout inside and is therefore not a typical tunnel.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The main file to run the simulation of the
% roundabout inside a tunnel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all; clc;
global global_info; % user data
global_info.PRINT_LOOP_NUMBER = 0;

% set stop as large number, because we manually stop when all vehicles
% have exited the roundabout.
global_info.STOP_AT = 100000000000;

% use counter to limit the amount of vehicles that can be inside the roundabout
% simultaneously since more than 4 is difficult.
global_info.VEHICLES_INSIDE_ROUNDABOUT = 0;

% Exit directions from the junction:
global_info.EXIT_DIR = {'exitEast' 'exitTunnel' 'exitWest'};
exitDirections = [1 2 3];
eastVehicles = ceil(80);
tunnelVehicles =ceil(436);
westVehicles = ceil(378);

global_info.TOTAL_NUMBER_OF_VEHICLES = eastVehicles + tunnelVehicles + westVehicles;

% East arm details
global_info.EAST_GEN_FIRING = rDivVehicles(eastVehicles, 1800);
global_info.EAST_E_DIR = ...
    generateExitforVehicles(exitDirections, [0 0.43 0.57],eastVehicles);
```

```
% Tunnel arm details
global_info.TUNNEL_GEN_FIRING = rDivVehicles(tunnelVehicles, 1800);
global_info.TUNNEL_E_DIR = ...
    generateExitforVehicles(exitDirections, [0.45 0 0.55],tunnelVehicles);

% West arm details
global_info.WEST_GEN_FIRING = rDivVehicles(westVehicles, 1800);
global_info.WEST_E_DIR = ...
    generateExitforVehicles(exitDirections, [0.71 0.29 0],westVehicles);


% create petri net structure
pns = pnstruct({'east_arm_pdf','tunnel_arm_pdf','west_arm_pdf',...
    'roundabout_in_tunnel_pdf', 'conn_pdf'});

% set initial tokens in places
dyna.m0 = {'pEastBuffer', eastVehicles,'pTunnelBuffer', tunnelVehicles,'pWestBuffer',
westVehicles};

% set firing times
dyna.ft = {'tEastEnterRoundabout',1.5, 'tTunnelEnterRoundabout',1.5,...
    'tWestEnterRoundabout',1.5,...
    'tToTunnelEast',2, 'tToTunnel',2,...
    'tToTunnelWest',2,'tToWest',2,...
    'tEastExitRoundabout',4,'tTunnelExitRoundabout',4,...
    'tWestExitRoundabout',4,...
    'allothers', 0.1};

% set priorities
dyna.ip = {'tEastExitRoundabout', 1,'tTunnelExitRoundabout', 1,'tWestExitRoundabout',1};

prnsys(pns, dyna);
pni = initialdynamics(pns, dyna);

% perform simulation run
sim = gpensim(pni);
% plot the results
figure;
plotp(sim, {'pEastQueue', 'pTunnelQueue', 'pWestQueue',...
    });

figure;
plotp(sim, {'pL1Place1', 'pL1Place2', 'pL1Place3', 'pL1Place4', 'pL1Place5',...
    });

figure;
plotp(sim, {'pEastExit', 'pTunnelExit', 'pWestExit',...
    });

classtype = pnclass(pns);
pns = pnstruct('roundabout_in_tunnel_pdf');
PI = pinvariant(pns);
TI = tinvariant(pns);
```

COMMON_POST

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The common post-function for this simulation. In this we see if all
% vehicles has arrived at their destination and stop the simulation.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [] = COMMON_POST(transition)

if (isequal(transition.name(6:end), 'ExitRoundabout') || (isequal(transition.name(8:end),
'ExitRoundabout') || (isequal(transition.name,'tEastExitTunnel'))))

    global global_info;

    if or(isequal(transition.name(6:end), 'ExitRoundabout'), isequal(transition.name(8:end),
'ExitRoundabout'))
        global_info.VEHICLES_INSIDE_ROUNDABOUT = global_info.VEHICLES_INSIDE_ROUNDABOUT - 1;
    end

    % this sees if the simulation is done finniched
    eastExit = get_place('pEastExit');
    tunnelExit = get_place('pTunnelExit');
    westExit = get_place('pWestExit');
    tokenSum = eastExit.tokens + tunnelExit.tokens + westExit.tokens;
    disp(strcat('tokenSum: ', num2str(tokenSum)));
    if ge(tokenSum, global_info.TOTAL_NUMBER_OF_VEHICLES)
        % The simulation is finnished since all vehicles has
        % reached their exit destination.
        disp('STOPPING SIMULATION, ALL CARS ARE THROUGH');
        global_info.STOP_SIMULATION = 1;
        return
    end
end
```

COMMON_PRE

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This is the common pre-function in the simulation. It's
% used to set several similar pre-files into one and make sure the model
% is in the rigth state when beginning.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [fire, transition] = COMMON_PRE(transition)

if gt(strfind(transition.name, 'EnterRoundabout'), 0)
    global global_info;
    % do not let vehicles into the roundabout if there is not enough
    % capacity (The limit is set to 3 as it's duty of givaway is a problem)
    if gt(global_info.VEHICLES_INSIDE_ROUNDABOUT, 3)
       fire = 0;
       return;
    end

    % loooking for transitions to the left because of duty of givaway
    % if they are firing vehicles can't enter the roundabout
    if eq(transition.name(2), 'E')
       if or(is_firing('tToEast'),is_firing('tToMid'))
           fire = 0;return;
```

```
        end
    elseif eq(transition.name(2), 'T')
        if or(is_firing('tToTunnel'),is_firing('tToTunnelEast'))
            fire = 0;return;
        end
    elseif eq(transition.name(2), 'W')
        if or(is_firing('tToWest'),is_firing('tToTunnelWest'))
            fire = 0;return;
        end
    end

    % vehicle enters into the roundabout, the action increase
    % the overall counter
    global_info.VEHICLES_INSIDE_ROUNDABOUT = global_info.VEHICLES_INSIDE_ROUNDABOUT + 1;
    fire = 1;

elseif gt(strfind(transition.name, 'GoToFrontOfQueue'),0)
    if eq(transition.name(2), 'E')
        queueName = strcat('p', transition.name(2:5), 'Queue', transition.name(22:end));
        firstInQueueToken = tokenArrivedEarly(queueName, 1);
        transition.selected_tokens=firstInQueueToken;

        fire = (firstInQueueToken);return;

    elseif eq(transition.name(2), 'W')
        queueName = strcat('p', transition.name(2:5), 'Queue', transition.name(22:end));
        firstInQueueToken = tokenArrivedEarly(queueName, 1);
        transition.selected_tokens=firstInQueueToken;

        fire = (firstInQueueToken);return;
    elseif eq(transition.name(2), 'T')
        queueName = strcat('p', transition.name(2:7), 'Queue', transition.name(24:end));
        firstInQueueToken = tokenArrivedEarly(queueName, 1);
        transition.selected_tokens=firstInQueueToken;

        fire = (firstInQueueToken);return;
    end


elseif or(isequal(transition.name(6:end), 'ExitRoundabout'),(isequal(transition.name(8:end),
'ExitRoundabout')))
    % check if someone is exiting the roundabout
    if eq(transition.name(2), 'E')
        tokID = tokenAnyColor('pRoundaboutMid', 1, {'exitEast'});
        %disp(tokID)
    elseif eq(transition.name(2), 'T')
        tokID = tokenAnyColor('pRoundaboutEast', 1, {'exitTunnel'});
        %disp(tokID)
    elseif eq(transition.name(2), 'W')
        tokID = tokenAnyColor('pRoundaboutTunnel', 1, {'exitWest'});
        %disp(tokID)
    end

    transition.selected_tokens = tokID;
    fire = (tokID);

else
    fire=1;
```

```
end
end
```

Roundabout Petri Net Definition File

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Petri net definition file of roundabout
% inside the tunnel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [png] = roundabout_in_tunnel_pdf()

png.PN_name = 'A PetriNet model for a roundabout in a tunnel';

png.set_of_Ps =
{'pRoundaboutEast','pRoundaboutTunnelEast','pRoundaboutTunnel','pRoundaboutTunnelWest',...
    'pRoundaboutWest','pRoundaboutMid',...
    'pEastExit','pTunnelExit','pWestExit',};

png.set_of_Ts = {'tEastEnterRoundabout', 'tEastExitRoundabout',...
    'tTunnelEnterRoundabout','tTunnelExitRoundabout',...
    'tWestEnterRoundabout', 'tWestExitRoundabout',...
    'tToTunnelEast','tToTunnel',...
    'tToTunnelWest','tToWest',...
    'tToMid','tToEast'};

png.set_of_As = {'tEastEnterRoundabout', 'pRoundaboutEast', 1,...
    'pRoundaboutEast', 'tTunnelExitRoundabout', 1,...
    'tTunnelExitRoundabout','pTunnelExit',1,...
    'pRoundaboutEast', 'tToTunnelEast', 1,...
    'tToTunnelEast', 'pRoundaboutTunnelEast', 1,...
    'pRoundaboutTunnelEast', 'tToTunnel', 1,...
    'tToTunnel', 'pRoundaboutTunnel', 1,...
    'tTunnelEnterRoundabout', 'pRoundaboutTunnel', 1,...
    'pRoundaboutTunnel', 'tWestExitRoundabout', 1,...
    'tWestExitRoundabout','pWestExit',1,...
    'pRoundaboutTunnel', 'tToTunnelWest', 1,...
    'tToTunnelWest', 'pRoundaboutTunnelWest', 1,...
    'pRoundaboutTunnelWest', 'tToWest', 1,...
    'tToWest', 'pRoundaboutWest', 1,...
    'tWestEnterRoundabout', 'pRoundaboutWest', 1,...
    'pRoundaboutWest', 'tToMid', 1,...
    'tToMid', 'pRoundaboutMid', 1,...
    'pRoundaboutMid', 'tEastExitRoundabout', 1,...
    'tEastExitRoundabout','pEastExit',1,...
    'pRoundaboutMid','tToEast', 1,...
    'tToEast', 'pRoundaboutEast', 1,...
    };

png.set_of_Is = {'pRoundaboutTunnelEast', 'tTunnelEnterRoundabout', 1,...
    'pRoundaboutTunnelWest', 'tWestEnterRoundabout', 1,...
    'pRoundaboutMid', 'tEastEnterRoundabout', 1,...
    'pRoundaboutTunnel', 'tTunnelEnterRoundabout', 1,...
    'pRoundaboutWest', 'tWestEnterRoundabout', 1,...
    'pRoundaboutEast', 'tEastEnterRoundabout', 1,...
    'pRoundaboutTunnel', 'tToTunnel', 1,...
```

```
    'pRoundaboutTunnelWest', 'tToTunnelWest', 1,...
    'pRoundaboutWest', 'tToWest', 1,...
    'pRoundaboutMid', 'tToMid', 1,...
    'pRoundaboutEast', 'tToEast', 1,...
    'pRoundaboutTunnelEast', 'tToTunnelEast', 1};
end
```

East_Arm

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Petri net definition file of the east portion arm of the
% simulation containg a roundabout in the tunnel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [png] = east_arm_pdf()

png.PN_name = 'Petri Net definition for the east arm of the roundabout in a tunnel';

png.set_of_Ps = {'pEastQueue', 'pEastBuffer'};

png.set_of_Ts = {'tEastEnterQueueGEN', 'tEastGoToFrontOfQueue'};

png.set_of_As = {'pEastQueue','tEastGoToFrontOfQueue',1,...
    'tEastEnterQueueGEN', 'pEastQueue', 1,...
    'pEastBuffer', 'tEastEnterQueueGEN', 1,};

png.set_of_Is = {'pEastQueue','tEastEnterQueueGEN', 10,};
```

East Enter Queue Generator

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Used to introduce the tokens into the junction at predefined
% times. In additon it tags the tokens with a exit direction.
%
% Some of this code is "borrowed" from the GPenSim manual
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [fire, transition] = tEastEnterQueueGEN_pre(transition)

global global_info;
% the firings are done if both "EAST_GEN_FIRING"
% or "EAST_E_DIR" is emppty

if or(isempty(global_info.EAST_GEN_FIRING),isempty(global_info.EAST_E_DIR))
    fire = 0; return;
end
time_to_generate_token = global_info.EAST_GEN_FIRING(1);
ctime = current_time();
exitDirection = global_info.EAST_E_DIR(1);
% if time to fire, then remove time
% from variable and fire
if ge(ctime, time_to_generate_token)
    if ge(length(global_info.EAST_GEN_FIRING),2)
        global_info.EAST_GEN_FIRING = ...
            global_info.EAST_GEN_FIRING(2:end);
```

```
    else
        global_info.EAST_GEN_FIRING = [];
    end
    if ge(length(global_info.EAST_E_DIR), 2)
        global_info.EAST_E_DIR = ...
            global_info.EAST_E_DIR(2:end);
    else
        global_info.EAST_E_DIR = [];
    end
    fire = 1;
else % this means no time to fire
    fire = 0;
end

if eq(fire,1)
    % This taggs the token with an exit direection
    transition.new_color = global_info.EXIT_DIR{exitDirection};
end
```

West Arm

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Petri net definition file of the west portion arm of the
% simulation containg a roundabout in the tunnel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [png] = west_arm_pdf()
png.PN_name = 'Petri Net definition for the tunnel before the roundabout';

png.set_of_Ps = {'pWestQueue', 'pWestBuffer'};

png.set_of_Ts = {'tWestEnterQueueGEN', 'tWestGoToFrontOfQueue'};

png.set_of_As = {'pWestQueue','tWestGoToFrontOfQueue',1,...
    'tWestEnterQueueGEN', 'pWestQueue', 1,...
    'pWestBuffer', 'tWestEnterQueueGEN', 1,};

png.set_of_Is = {'pWestQueue','tWestEnterQueueGEN', 10,};
```

West Enter Queue Generator

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Used to introduce the tokens into the junction at predefined
% times. In additon it tags the tokens with a exit direction.
% Some of this code is "borrowed" from the GPenSim manual (Davidrajuh, 2014)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [fire, transition] = tWestEnterQueueGEN_pre(transition)

global global_info;

% the firings are done if both "WEST_GEN_FIRING"
% or "WEST_E_DIR" is emppty
if or(isempty(global_info.WEST_GEN_FIRING),isempty(global_info.WEST_E_DIR))
    fire = 0; return;
end
```

```
time_to_generate_token = global_info.WEST_GEN_FIRING(1);
ctime = current_time();
exitDirection = global_info.WEST_E_DIR(1);
% if time to fire, then remove time
% from variable and fire

if ge(ctime, time_to_generate_token)
    if ge(length(global_info.WEST_GEN_FIRING),2)
        global_info.WEST_GEN_FIRING = ...
            global_info.WEST_GEN_FIRING(2:end);
    else
        global_info.WEST_GEN_FIRING = [];
    end
    if ge(length(global_info.WEST_E_DIR), 2)
        global_info.WEST_E_DIR = ...
            global_info.WEST_E_DIR(2:end);
    else
        global_info.WEST_E_DIR = [];
    end
    fire = 1;
else % this means no time to fire
    fire = 0;
end

if eq(fire,1)
    % This taggs the token with an exit direection
    transition.new_color = global_info.EXIT_DIR{exitDirection};
end
```

Tunnel Arm

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Petri net definition file of north-going arm which is the furtest
% stretch of tunnel in the simmulation with
% a roundabout in a tunnel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [png] = tunnel_arm_pdf()

png.PN_name = 'A Petri Net definition for the tunnel arm of the roundabout in a tunnel';

png.set_of_Ps = {'pTunnelBuffer', 'pTunnelQueue'...
    'pL1Place1', 'pL1Place2', 'pL1Place3', 'pL1Place4', 'pL1Place5'};

png.set_of_Ts = {'tTunnelEnterQueueGEN','tTunnelGoToFrontOfQueue',...
    'tL1EnterTunnel','tL1ToPlace2', 'tL1ToPlace3',...
    'tL1ToPlace4', 'tL1ToPlace5'};

png.set_of_As = {'pTunnelBuffer','tL1EnterTunnel',1,...
    'tL1EnterTunnel','pL1Place1',1,...
    'pL1Place1', 'tL1ToPlace2', 1,...
    'tL1ToPlace2', 'pL1Place2', 1,...
    'pL1Place2', 'tL1ToPlace3', 1,...
```

```
    'tL1ToPlace3', 'pL1Place3', 1,...
    'pL1Place3', 'tL1ToPlace4', 1,...
    'tL1ToPlace4', 'pL1Place4', 1,...
    'pL1Place4', 'tL1ToPlace5', 1,...
    'tL1ToPlace5', 'pL1Place5', 1,...
    'pL1Place5', 'tTunnelEnterQueueGEN', 1,...
    'tTunnelEnterQueueGEN', 'pTunnelQueue', 1,...
    'pTunnelQueue', 'tTunnelGoToFrontOfQueue',1,...
    };

png.set_of_Is = {'pTunnelQueue','tTunnelEnterQueueGEN', 10,...
    'pL1Place1', 'tL1EnterTunnel', 1,...
    'pL1Place2', 'tL1ToPlace2', 1,...
    'pL1Place3', 'tL1ToPlace3', 1,...
    'pL1Place4', 'tL1ToPlace4', 1,...
    'pL1Place5', 'tL1ToPlace5', 1,};
```

Tunnel Enter Queue Generator

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Used to introduce the tokens into the junction at predefined
% times. In additon it tags the tokens with a exit direction.
%
% Some of this code is "borrowed" from the GPenSim manual (Davidrajuh, 2014)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [fire, transition] = tTunnelEnterQueueGEN_pre(transition)

global global_info;


% the firings are done if both "TUNNEL_GEN_FIRING"
% or "TUNNEL_E_DIR" is emppty
if or(isempty(global_info.TUNNEL_GEN_FIRING),isempty(global_info.TUNNEL_E_DIR))
    fire = 0; return;
end

time_to_generate_token = global_info.TUNNEL_GEN_FIRING(1);
ctime = current_time();
exitDirection = global_info.TUNNEL_E_DIR(1);

% if time to fire, then remove time
% from variable and fire

if ge(ctime, time_to_generate_token)
    if ge(length(global_info.TUNNEL_GEN_FIRING),2)
        global_info.TUNNEL_GEN_FIRING = ...
            global_info.TUNNEL_GEN_FIRING(2:end);
    else
        global_info.TUNNEL_GEN_FIRING = [];
    end
    if ge(length(global_info.TUNNEL_E_DIR), 2)
        global_info.TUNNEL_E_DIR = ...
            global_info.TUNNEL_E_DIR(2:end);
    else
        global_info.TUNNEL_E_DIR = [];
```

```
    end
    fire = 1;
else % this means no time to fire
    fire = 0;
end

if eq(fire,1)
    % This taggs the token with an exit direection
    transition.new_color = global_info.EXIT_DIR{exitDirection};
end
```

Connecting Petri Net Definition code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Connecting the modules to eachother as one complete model
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [png] = conn_pdf()

png.PN_name = 'Connects the junction arms to the junction';

png.set_of_Ps = {'pEastFrontOfQueue','pTunnelFrontOfQueue',...
    'pWestFrontOfQueue'};

png.set_of_Ts = {};

png.set_of_As = {'pEastFrontOfQueue','tEastEnterRoundabout',1,...
    'tEastGoToFrontOfQueue', 'pEastFrontOfQueue', 1,...
    'pWestFrontOfQueue','tWestEnterRoundabout',1,...
    'tWestGoToFrontOfQueue', 'pWestFrontOfQueue', 1,...
    'tTunnelGoToFrontOfQueue', 'pTunnelFrontOfQueue', 1,...
    'pTunnelFrontOfQueue','tTunnelEnterRoundabout',1,...
    };

png.set_of_Is = {'pEastFrontOfQueue', 'tEastGoToFrontOfQueue', 1,...
    'pTunnelFrontOfQueue', 'tTunnelGoToFrontOfQueue', 1,...
    'pWestFrontOfQueue', 'tWestGoToFrontOfQueue', 1,};
```

Sum and plot function when there are multiple lanes

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Function used to sum the tokens from a
% list of places, and plot them as one line.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [] = SumandPlot( placeNames )
% extract the places
pHist = extractp(placeNames);
preliminar_Result = zeros(length(pHist), 2);
preliminar_Result(:,[1]) = pHist(:, [1]);

% sum the tokens
for i = 1:length(pHist)
    for j = 2: length(placeNames) + 1
        preliminar_Result(i,2) = preliminar_Result(i,2) + pHist(i,j);
    end
```

```
end

% plot the result
times = preliminar_Result(2:length(pHist),1);
tokens_in_place = preliminar_Result(2:length(pHist),2:2);
plot(times,tokens_in_place,'-h', 'linewidth', 0.5, 'MarkerSize', 5 );
grid on;
xlabel('Seconds');
ylabel('Total amount of tokens');
end
```

Random dividing of tokens on the time of simulation

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Randomly divide the amount of tokens that is generated from one of the
% entries across a given time period.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [ output ] = rDivVehicles( amountOfVehicles, time )

output = zeros(1,amountOfVehicles);
for i = 1:amountOfVehicles
    output(i) = rand() * time;
end

output = sort(output);
end
```

Generate Exit for the Vehicles

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Function used to generate N numbers from with a set distribution.
% Used to decide which vehicles exit on a location in the junction.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [result] = generateExitforVehicles(numbers,distribution, N)

result = [];

for index = 1:length(numbers)
    tempResult = ones(1,ceil(distribution(index)*N));
    tempResult = tempResult .* numbers(index);
    for j = 1:length(tempResult)
        result = [result tempResult(j)];
    end
end

result = result(randperm(length(result)));
```