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DESIGNING THE WESTERSCHELDETUNNEL TOLL PLAZA USING A COMBINATION OF QUEUEING AND SIMULATION

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ABSTRACT

This paper describes how a combined queueing and simulation study was successfully executed for the design of a toll plaza. The objectives of the study were twofold:

- to configure the types of toll booths with multiple payment functionalities (cash, credit cards, and electronic payment).
- to determine the number of toll booths for each type.

The model was also used to validate the spacing, safety, and accessibility of the toll plaza.

A hybrid approach of simulation and queueing theory proved to be a powerful method in analyzing the queueing processes of the toll plaza. This approach combined the insights from queueing theory with the practical applicability of simulation. Queueing theory provided the conceptual framework and limited the number of variants to be examined, while simulation was used to compare and evaluate the variants.

The study showed that fewer toll booths were needed when different payment systems were separated, as a combination of different payment systems at one toll booth would substantially enlarge the *variability* of service times. This variability appeared to dominate the '*inefficiency*' of separate toll booths which may seem counterintuitive. Consequently, the initial design had to be completely redesigned.

1 INTRODUCTION

1.1 Background

In the southwest of the Netherlands, a tunnel will be built underneath the 'Westerschelde' river. The 4.1 mile tunnel is expected to be open to traffic in the year 2003, with approximately 12,000 vehicles using it daily. The costs of building the tunnel are estimated at nearly $1 billion and drivers will have to pay a toll to use the tunnel.

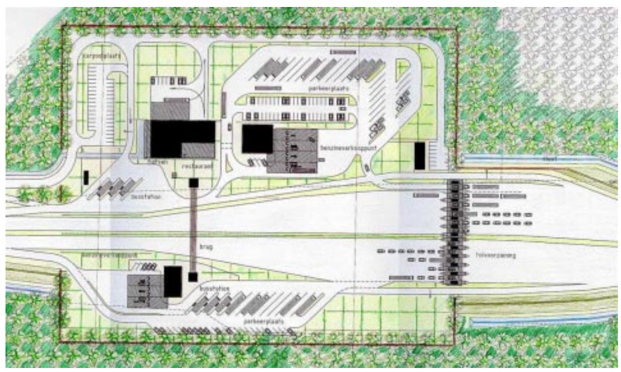

Figure 1: Initial Design of the Toll Plaza.

At the northern end of the tunnel, a toll plaza will be constructed where traffic moving in both directions will have to pay a toll. The toll plaza, shown in Figure 1, will consist of a number of diverging lanes leading to toll booths, after which the lanes converge again. In addition, a service area on both sides of the main road will be part of the toll plaza. The service area will contain two gas stations, parking area for both cars and trucks, a bus station for public transportation, and a restaurant.

The design of the toll plaza had already been completed by an architect. A thorough validation of the design was the last step before final approval of the design, after which the construction of the toll plaza would immediately start. The validation was required to verify the capacity and functionality of the infrastructure of the toll plaza. The tunnel management company N.V. Westerscheldetunnel did not want to encounter any unpleasant surprises after building the toll plaza. Incontrol

Business Engineers and the Traffic Research Centre were therefore assigned to validate the design of the toll plaza.

1.2 Goal and Project Objectives

The goal of the project was to ensure that the toll plaza could handle the traffic flows without any problems. Project objectives were:

- to determine the number and different types of toll booths in terms of single or multiple payment functionalities; and,
- to validate the infrastructural design of the toll plaza with regard to spacing, safety, and accessibility.

1.3 Number of Toll Booths

In the initial toll plaza design, space had been reserved for five toll booths in either direction. The number of toll booths had to be determined in order to process peak traffic hours without long waiting times. Two extreme but natural options would be:

- to offer all types of payment systems in all booths.
- to have separate toll booths for each payment type.

Clearly, offering all payment systems at all toll booths would seem more efficient and provide more flexibility during the operation. However, it could also be more costly as more operators may have to be employed. The electronic payment systems do not require manual assistance. Separate payment toll booths, in contrast, may require more toll booths in total and lead to longer waiting times.

1.4 Spacing, Safety, and Accessibility

The integral design of the toll plaza, which included the service area, also had to be validated on spacing, safety, and accessibility.

Only a small area was available for the toll plaza. Yet, traffic should not encounter any bottlenecks on the roads, junctions, or parking lots. It was therefore important to check whether the spacing of the infrastructure would be sufficient to enable drivers to drive with ease. Moreover, the parking areas and gas stations should also have enough capacity.

Safety of vehicles on the toll plaza was also an important issue, as was the accessibility of the toll plaza. Any blocked traffic flows would be unacceptable. In addition, drivers should be able to find their way in a logical and intuitive way.

2 WHY SIMULATION?

To address the objectives, three methods were available:

- analytical queueing theory,
- traditional traffic models, and
- simulation.

The nature and the complexity of the toll plaza required a method capable of dealing with both the queueing processes and the traffic flows at the toll plaza.

Section 2.1, explains why the queueing processes at the toll plaza were too complex for analytical queueing methods. Furthermore, existing traffic simulation tools appeared to be too rigid and could not handle the wide variety of traffic processes at the toll plaza, which is explained in section 2.2.

Consequently, the tunnel management company decided to have the design validated by simulation. The Arena template methodology was selected because of its generic, open, and flexible structure.

2.1 Complex Queueing Process

At the toll plaza, arriving vehicles have to choose a toll booth depending on their payment system and the queueing length at the toll booths that offered the desired payment system. Analyzing the performance of the queueing process at the toll booths therefore demanded a flexible method, since a wide variety of queueing configurations under different scenarios had to be analyzed.

One option would be to separate the lanes and to offer only one type of payment system at every toll booth (see Figure 2). The disadvantage of a separate lane system is that certain toll booths can be underutilized while others will be overloaded. This can be inefficient in operational usage. Analytical queueing systems can predict the behavior of separate lane queueing system well.

Another option would be to offer all payment systems at all toll booths and have the vehicles queue in one line. Each toll booth would accept cash, credit cards, and electronic payment. The advantage in this case is that it provides more operational flexibility while it also increases the efficiency (utilization) of the toll booths. The disadvantage, however, is that the wide range of service times introduces variability. As variability in service times is one of the main causes for queues to arise, this disadvantage can dominate the gain in efficiency. A more detailed quantitative study taking into account the actual numbers is therefore required.

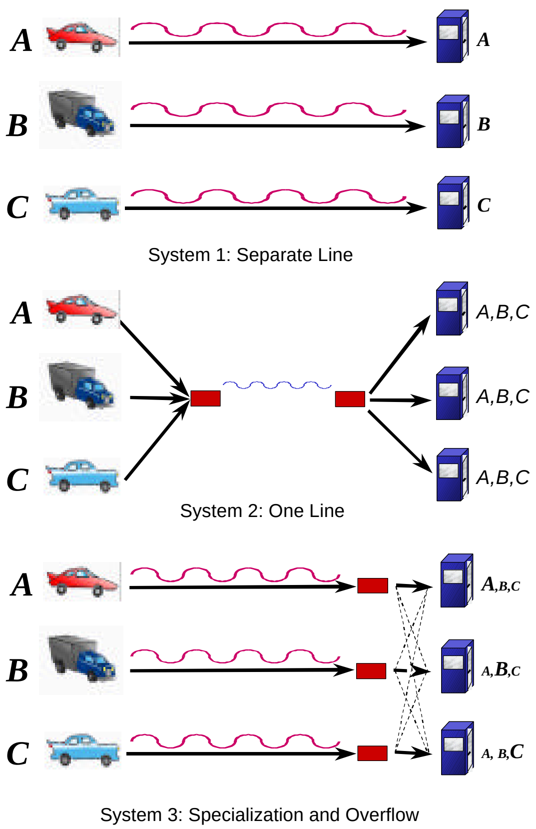

Figure 2: Possible Queueing Systems at the Toll Booths.

In fact, by combining both insights, a third option might even be more attractive by using specialized lanes to keep the variability per lane to a minimum and by also allowing 'overflow' when one or more ticket booths are temporarily underutilized. In section 3.3, some results for these three options will be provided which support the importance of these insights.

Accordingly, the challenge is to find a combination of separate or mixed payment systems at each toll booth reducing variance in service times to a minimum on one hand while still striving for efficiency and balanced workloads on the other. Furthermore, drivers should not be confused and simple directions are required.

Unfortunately, analytical queueing methods are not sufficiently capable to predict queueing systems with specialization in combination with overflow. At this point, simulation comes in as a *necessary* tool to evaluate and optimize the concepts and results from queueing theory.

2.2 Dynamic Traffic Flows

A variety of traffic situations at the toll plaza had to be analyzed: high speed traffic flows at the main roads, junctions, exits, designated roads for public transportation, and the roads on the service areas. Some of these flows seemed to be conflicting and could be possible bottlenecks, but it was unclear whether this would cause any problems. Quantitative analysis was required to make solid judgements about the traffic infrastructure of the toll plaza. However, traditional traffic models tools appeared to be too rigid to handle the wide variety of traffic processes at the toll plaza. A more flexible tool was required.

Therefore, the Traffic-Flow template was used to model the traffic flows of the toll plaza. Incontrol Business Engineers developed the Traffic-Flow template based on experiences from several infrastructural and traffic projects. The Arena based template contains predefined traffic building blocks, representing roads and junctions. Different infrastructural configurations could be constructed in a short period of time. The template focuses on road capacity and conflicting usage of infrastructure. Traffic rules can be added to regulate vehicle movements. Teunisse and Hooghiemstra (1998) have extensively described the benefits of using template methodology.

The open structure of the Traffic-Flow template facilitated the full integration with standard Arena code used for modeling specific elements of the toll plaza. It was therefore possible to integrate the queueing processes at the toll booths with the traffic processes at the service area.

Visual Basic for Applications was used to import input data into, and export output data from the simulation model. This enabled the different variants and configurations to be quickly run and analyzed. All simulation results were directly available in easy-to-read Excel format.

3 WHY SIMULATION IN COMBINATION WITH QUEUEING?

3.1 Queueing Behavior

Delays and queueing problems are most common in daily-life situations, whether in a supermarket, a bank, a ticket office, or in traffic. The stochastic characteristics of queueing processes make it difficult to fully predict queueing behavior.

Waiting times in queueing systems are not linear. When the workload, or occupancy rate, of a server doubles, waiting times may quadruple if not more. When the workload of a server is higher than 90 percent, waiting times can become 10 times as large as the actual service or handling times.

After workload, a second main reason for waiting times is the notion of variability. For example, 4 arrivals at a single toll booth within a 5 minute period with an average handling time of one minute each will not have to wait if they arrive at constant interarrival times of one minute apart and with constant handling time of one minute. However, the average waiting time will become 2 minutes should they arrive 'at random', thus with interarrival times of either more or less than one minute. Also, if the handling times varied, this average wait time can grow arbitrarily. Higher variability in arrival patterns or service times thus directly results in higher waiting times. To keep waiting times low as possible, it is thus important to keep the variability in service times as low as possible.

3.2 Simulation versus Queueing

Basically, there are two ways to analyze queueing issues: by traditional analytical queueing analysis or by simulation. Generally, these methods are used disjoint.

The advantage of queueing analysis is that it provides a conceptual framework and insights of how queueing systems behave. As such, it directs the way of thinking in complex queueing situations. However, queueing analysis is generally perceived as impractical, as it is based on exponential assumptions for arrival patterns and service times as well as is also highly limited in system complexity.

Simulation, in contrast, has proven to be a powerful and easily accessible modeling tool in highly complex queueing situations while allowing arbitrary input distributions. But, it lacks a conceptual framework and insights for design or optimization questions, such as selecting which variants or configurations to analyze.

3.3 Advantages of a Hybrid Approach

A hybrid queueing and simulation approach is therefore recommended for projects such as in this case (Van Dijk 1999). It combines the best of both methods: the conceptual framework and insights from queueing with the modeling and evaluation potential for complex real life situations by simulation. Queueing insights can limit the number of variants to be examined, while simulation compares and evaluates the different variants.

A review of the three options from section 2.1 for a fictitious traffic situation with three types of vehicles, labeled A, B, and C, as in Table 1, illustrates this combined approach. Based on the general insights from queueing theory, the second and third option have to be compared. However, due to the mixed services under option 2 and, even more the overflow under option 3, simulation is necessary to evaluate the performance.

Table 1: Arrivals and Service Times.

Vehicle Type	Arrivals (number/hour)	Service Time (minutes)
A	10	1
B	2	5
C	1	10

The results from simulation, as presented in Table 2, reveal the importance of this combined approach. For the majority of cars (Type A), the first option, separate lanes, is still by far the best. The more efficient option 2 (one line system) has an overall better performance, but by avoiding mixed services to a certain extent (option 3), the unit performance for all traffic types is improved.

Table 2: Waiting Times (in Seconds).

	Queueing System		
Vehicle Type	1	2	3
A	185	326	228
B	933	317	279
C	1856	313	274
Mean	426	323	239

This example illustrates the potential of the combined approach of queueing insights and simulation. Without queueing the third option as well as many more optional overflow variants would not have been considered. Without simulation the systems could not have been evaluated properly.

Furthermore, queueing insights drastically limit the number of variants to be evaluated. Analytical queueing results check the simulation model correctness (verification) for specific cases. Accordingly, queueing helps to build confidence. The next section reports how similar steps have been followed for the toll plaza project.

4 DETERMINING THE NUMBER OF TOLL BOOTHS REQUIRED

4.1 Description of the System

An important part of the simulation study was to provide valid input data for the simulation model, such as traffic forecasts, service times, and parking times. The traffic forecasts used in the simulation model were based on external traffic forecast models. Given the direct relation between the input data and the performance of the toll system, it was important that the input data and assumptions were accurate.

When historical or realistic data were not available 'worst case' assumptions were made. If the toll plaza could handle the worst case scenarios without any problems, it should also be able to handle the realistic situation. The following input data were collected:

<u>Payment system configuration.</u> Different payment systems will have to be offered at the toll plaza: cash, credit card, debit card, and electronic payment (ETC). Combinations of payment systems at one booth are also considered. The percentage of drivers expected to use a certain payment system is therefore an important input parameter (see Table 3). The tunnel management

Table 3: Distribution of Preferred Payment Systems during a Tourist Peak Hour. (%)

	Cars	Motorcycles	Trucks
ETC	55	N.A.	70
Cash	22.5	50	15
Debit Card	11.25	25	7.5
Credit Card	11.25	25	7.5

company expects approximately 60 to 70 percent of the vehicles to pay electronically, in the long term.

In the tourist season, a much higher percentage of the vehicles are expected to pay with cash. Cash payments are handled manually by a toll booth operator. The other payment systems can be processed automatically.

- Arrival Pattern. The traffic forecasts were based on a non-tourist and a tourist peak hour traffic arrival pattern, for the year 2010 (see Table 4). The non-tourist peak hour assumed an evening peak hour, with about 500 vehicles per hour in each direction. Approximately 20 percent of the vehicles are expected to be trucks.

Table 4: Number of Vehicles Arriving per Hour in the Direction North-South, in 2010. (DHV,1998)

	Non-tourist Peak hour	Tourist Peak hour
Cars	370	436
Motor cycles	4	6
Trucks	103	103
Total	477	543

As the Westerschelde area is a popular tourist region, tourist peak hours are expected in the summer. During a tourist peak hour, approximately 550 vehicles per hour are expected to pass the tunnel in either direction.

As a complicating factor, vehicles are likely to arrives in batches, as faster vehicles are not able to pass slower vehicles on the roads from the tunnel towards the toll plaza.

- Service times. Each payment system has its own service time (See Table 5). For example, paying cash will take much longer than paying electronically with an electronic tag installed in a vehicle. The question is which payment system, or which mix to locate at which booths. The service times also depend on the type of vehicle.

Before operating the simulation model, a sensitivity test proved that the important input parameters were not sensitive at the traffic intensities analyzed. A small change in the input parameters did not result in significant changes in the performance of the toll plaza.

Table 5: Average Service Times per Vehicle Type (in seconds).

	Cars	Motorcycles	Trucks
ETC	3.8	N.A.	5.1
Cash	7.5	7.5	13.1
Debit Card	20.0	20.0	23.0
Credit Card	4.5	6.0	10.1

4.2 Performance Indicators

The following performance indicators were considered:

- Waiting times. Clearly, waiting time is the most important indicator. Not only the average waiting time, but more importantly the distribution of waiting times were of interest. In particular, the percentage of vehicles having to wait a certain amount of time. For example, say the average waiting time at a toll booth is 20 seconds, which is acceptable. However, an analysis of the waiting times at the same toll booth may show that 5% of the drivers would have to wait longer than 10 minutes, which would be unacceptable. The average waiting time does not show the long waiting times that are compensated by shorter waiting times.
- Queue lengths. As another indicator of operational importance, queue sizes have to be monitored. Queue sizes depend on service times, waiting times, and arrival patterns of vehicles. The lanes heading towards the toll booths should be long enough to accommodate long queues. This is where the difference between vehicle categories becomes important. A large percentage of trucks are expected to pay electronically, which could cause longer queue lengths at the ETC toll booth. Also, at some toll booths, long queues could block exits to the service area. In the simulation model, incoming vehicles would select the toll booth with the shortest queue length, provided the toll booth offers the payment needed.
- Workload. The workload of a toll booth is the percentage of time that a toll booth is serving drivers. Clearly, from an operational perspective, low workloads are not desirable while high workloads may cause excessive waits. Hence, good balanced workloads over

the different types of toll booths had to be achieved.

4.3 Toll Booth Configurations Variants

Various toll booth configurations were analyzed. A configuration is characterized by the number of toll booths per direction, and the payment functionalities per toll booth.

Each variant had to be analyzed for a tourist and a non-tourist peak hour. Each direction had to be calculated separately, as the design of the toll plaza was unsymmetrical while also the traffic forecasts per direction differed.

Ten variants were analyzed. First, the number of toll booths was determined. Next, the optimal combination of payment functionalities of the toll booths was investigated. New variants were defined based on the results of the first variants in line with queueing insights.

4.4 Simulation Results of Variants

The simulation study showed that fewer toll booths were required than planned in the initial design of the toll plaza. This reduction was achieved by separating the payment systems to reduce the variance in service times at every toll booth.

At the same time, the simulation study also determined that one group of payment systems with similar service times could be grouped. Together, this reduced the number of toll booths required without causing a decrease in service level. This grouping of payment systems implicitly enabled incoming traffic to switch to a toll booth with short waiting times.

In Table 6 and 7, the two variants of a mixed and a separate payment system toll booth configuration are compared. Important to realize is that roughly 65% of all payments are electronic (see Table 3). In a mixed payment system, nearly half of the electronically paying vehicles choose the mixed toll booth, and experience a relatively long waiting time (on average 7.6 seconds). The other half of the electronically paying vehicles appear to pass the ETC toll booth with an average waiting time of 0.7 seconds. Consequently, the average waiting time for electronically paying vehicles as a group is approximately 4 seconds.

Table 6: Results for Mixed Payment Systems.

Toll Booth	Payment System	Work Load (%)	Wait Time (sec)	Queue Length (m)
1	ETC	23.3	0.7	2.5
2	Cash, Cards	52.9	5.2	5.1
3	Cash, Cards, ETC	66.1	7.6	8.1

In the separate lane system, in contrast, the average waiting time for electronically paying vehicles appears to be reduced to 2 seconds. Given the large percentage of vehicles paying electronically, this is a significant decrease in waiting times. As a result, the separate payment system has a better overall performance in comparison with the mixed payment system. For electronic payments, where the service times are significantly shorter, a separate '*electronic highway*' appeared to be the best option.

Table 7: Results for Separated Payment Systems.

Toll Booth	Payment System	Work Load (%)	Wait Time (sec)	Queue Length (m)
1	ETC	33	2	4.5
2	Cards	44	8.1	4.8
3	Cash	31	3	2.6

For the service area, one toll booth specifically designated in the initial design to access the service area appeared to be highly underutilized. Even during the tourist peak hour, it was used only 20% of time. In the advisory model, therefore, a payment machine at the service area was proposed.

5 VALIDATING THE INTEGRAL DESIGN

The configuration, dimensioning, and validation of the spacing, safety, and accessibility of the integral toll plaza were based on the quantitative results and the qualitative insights of the simulation model. To validate the design, the simulation model also had to critically look at the details of the design, resulting in a number of qualitative recommendations.

One of the initial requirements of the simulation model was that it was highly visual and animated, so that the model could later be used for promotional purposes. But the animation also appeared to be useful for other purposes. After the modeling phase, it was used to validate the simulation model. Traffic experts agreed that the simulation model reflected the actual situation of the toll plaza.

Moreover, animation was important in the validation of the integral design, as it revealed a number of flaws and illogical traffic flows in the design. The possibility of such conflicting traffic flows would not have been revealed without animation.

The validation of the integral design by animation produced the following results:

- <u>Compact design.</u> The design of the toll plaza was very compact. The main idea behind the design was to make it a square toll plaza in a limited area. The square shape of the toll plaza placed some severe constraints on the traffic flows. A longer shape of the toll plaza design would have ensured smoother traffic flows. With the square shape, traffic encountered sharp curves creating difficulties for vehicles to maneuver, especially for trucks.

- Sufficient capacity. At the service area, the traffic intensities were so low that no bottlenecks or problems caused by capacity shortage were found. The simulation study showed that no delays or queues would occur because of a capacity shortage. There was also enough parking capacity available.
- Long queues block roads. Long queues at a toll booth could block the exit to the toll plaza. There was also a possibility that a designated bus lane would be blocked when queues occurred. Although the likelihood of the long queues was low, it was a potential bottleneck.
- Unsymmetrical. The design of the toll plaza was not symmetrical. Vehicles coming from the north (west side) could first visit the service area before paying a toll, while vehicles from the south (eastern side), on contrast, would have to pay first before visiting the service area. This could potentially be confusing for drivers. It also appeared that the service area at the western side had fluent traffic flows without bottlenecks or dangerous junctions.
- Confusing directions. The eastern side of the toll plaza had a number of junctions and curves that could be dangerous for traffic. Without clear direction boards, it would be quite confusing for drivers to find their way in the eastern service area.
- Circulating traffic. At the eastern side of the service area, the roads and junctions enabled vehicles to circulate around the parking areas. This could lead to dangerous situations, as circulating traffic could easily conflict with incoming traffic.
- Gas station. Based on the input assumptions, it appeared that more fueling capacity was needed on the gas stations. For instance, a truck waiting in front of the gas station would automatically block the entrance of the service area.

In summary, the design appeared to contain a number of shortcomings, such as conflicting and potentially dangerous junctions. The functionalities and service levels required were not sufficiently met. Consequently, the tunnel management company came to the conclusion that a redesign of the toll plaza was required.

6 RESULT: COMPLETE REDESIGN OF THE TOLL PLAZA

Following the results of the simulation study, a brain storm session with all parties involved was organized, in which a new design was made (Figure 3). The major design changes were the following:

- Symmetrical design. The new design was made symmetrical with the east and the west side made identical. In this design, the traffic flows were more fluent, resulting in fewer potentially dangerous junctions at the toll plaza.

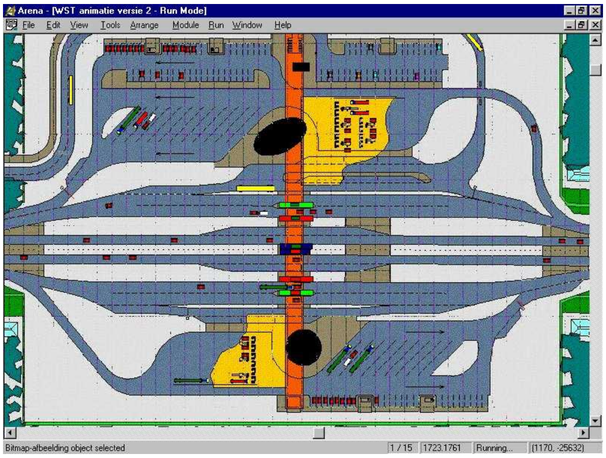

Figure 3: Simulation Model of the New Design of the Toll Plaza.

- Separate payment systems. As the simulation study showed that the toll booth for electronic payment should be separated from the other payment systems. An 'electronic highway' was introduced whereby a separate lane was designated for electronic payment.
- Ticket machine at service area. The simulation study also revealed the underutility of the toll booth designated for traffic to the eastern service area. Instead, ticket vending machines at the service area were suggested as an additional feature. Drivers would then have to insert their ticket into a vending machine at the exit gate of the service area.
- Fewer toll booths. In the new design, fewer toll booths would have to be set up. This would result in a smaller area required for the toll plaza and thus lower construction costs.

Only one toll booth on either side required an operator, leading to lower operating costs.

7 CONCLUSIONS: LESSONS LEARNED

To start the design of an infrastructural project such as a toll plaza, it is recommended to include simulation experts in the multidisciplinary team consisting of architects, traffic experts, and tunnel exploitation managers. By early involvement of simulation in the design phase of infrastructure projects pitfalls can be avoided and capacity characteristics can be determined.

To better understand the dynamic traffic and queueing processes for the toll plaza, a combination of simulation and queueing proved to be most powerful. Queueing provided the conceptual way of thinking and insights from which variants would be derived that were modeled and analyzed by simulation. Furthermore, it was also used for verification and dimensioning purposes of the simulation model. A hybrid usage of queueing and simulation is thus recommended. The quantitative and qualitative results prevented under- and over-dimensioning of the toll plaza. This, in turn, resulted in a cost reduction.

The Traffic-Flow template with traditional Arena building blocks proved most useful. Animation was very helpful to detecting bottlenecks in the dynamic traffic flows at the toll plaza.

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