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Limiting Nuisance for Traffic during the Refurbishment of the Heinenoord Tunnel in The Netherlands: In Search of Resilience Possibilities

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Abstract: The Heinenoord Tunnel in The Netherlands connects the Hoeksche Waard Island with the city of Rotterdam. The tunnel is 614 m long, consists of two unidirectional tubes (3 lanes each) and has an average daily traffic load of 92,100 vehicles. The tunnel was opened for traffic in 1969. The structure is basically still sound, but a full refurbishment of the installations and systems is required, because they are end of life. A long closure of the tunnel (or even one tube) is not possible, because alternative routes are scarce and require significant extra travel time, not suitable for the high traffic load. Thus, various scenarios were considered to assure the accessibility of the Hoeksche Waard during the works, scheduled for 2023-2024. Multi-criteria analyses were performed for each scenario, taking into account the total project cost, societal cost (due to extra travel time) and the total required time span for the works. Refurbishment through "parallel assembly" proved to be optimal. This concept means that the new installations and systems are installed next to the current ones, that will remain in service until the end phase of the refurbishment. The existing installations and systems are only dismantled after integral testing has shown that the completed new ones work properly. This approach allows most of the works to be carried out during a series of night and weekend closures of just one tube. This limits nuisance, because one driving direction is always left undisturbed, while the closure for the other driving direction takes place in low-traffic periods. This paper describes the applied method to select the optimal refurbishment approach, as well as the (partly unconventional) measures that are implemented to enhance the resilience of the tunnel system to assure as much availability for traffic as possible, also during future maintenance works.

Key words: Road tunnel, safety, refurbishment, resilience, traffic nuisance, social interests.

1. Introduction

RWS (Rijkswaterstaat) is the executive organisation of the Dutch Ministry of Infrastructure and Water Management. RWS develops and manages the main (state-owned) infrastructure in The Netherlands, like the primary road network, the primary waterways, as well as the main water systems. RWS's mission focuses on protection against flooding, sufficient clean water, a smooth and safe transport by road and water, reliable and useful information and a sustainable living environment. As such, RWS fulfils three social roles: as public-oriented network manager, leading project manager and effective crisis manager.

As part of the primary road network (highway network) RWS manages numerous bridges, viaducts and tunnels. One of these tunnels is the Heinenoord Tunnel. This paper deals with the refurbishment of that tunnel, taking place during a two-year period (2023-2024). Currently, the preparations for the refurbishment works are in full swing, involving detailed planning, design, measures to limit nuisance, coordination with stakeholders, applications for the required permits and an information campaign.

To limit the nuisance of the refurbishment works for the region and the through-traffic, various measures were considered and evaluated for their effectiveness,

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cost and other aspects. In other words, the characteristics of the existing tunnel system to be resilient for the refurbishment works were analysed for their potential effect. Additional measures to enhance resilience were also considered.

Working Group 2 of PIARC TC 4.4 on Tunnels defined road tunnel resilience as follows [1]:

"The ability of the tunnel system to prepare, plan for, resist, absorb, recover from, more successfully adapt to actual or potential negative effects of events or developments affecting the availability of a road tunnel in a timely and efficient way. In this context, an acceptable safety level is a mandatory constraint for the availability of the road tunnel".

Moreover, according to the PIARC Road Dictionary [2], the tunnel system can be defined as the whole of the structure, installations, internal and external infrastructure, operation and management organization of a road tunnel.

In this case, the refurbishment works are the event the Heinenoord Tunnel System should be resilient for.

2. Tunnel Location and Characteristics

The Heinenoord Tunnel crosses the Oude Maas River, just south of Rotterdam, as part of the A29 highway (see Figs. 1 and 2). The A29 is not only important for through-traffic, but also for local traffic, because it connects The Hoeksche Waard (a municipality as well as an island) to other parts of the Rotterdam region, including the seaport, the biggest and busiest in Europe.

The Hoeksche Waard Island (88,742 inhabitants, spread over various towns and villages) is surrounded by four rivers:

- The afore-mentioned Oude Maas river on the north side, crossed by the Heinenoord Tunnel for highway traffic (A29) and the smaller Second Heinenoord Tunnel for pedestrians, cyclists, mopeds and agricultural traffic (tractors);
- The Dordtsche Kil River on the east side, crossed by the Kil Tunnel for motorized traffic, pedestrians, cyclists and mopeds;
- The Hollands Diep River on the south side, crossed by the Haringvliet Bridge for highway traffic (A29);
- The Spui River on the west side, crossed by a ferry service for pedestrians, cyclists, mopeds and motorized traffic.

The Heinenoord Tunnel is by far the busiest river crossing, processing as much as 91,200 vehicles per day (counting both directions). In case of closure for traffic, the most suitable detour would be through the Kil Tunnel. But this route partly runs over a secondary road (N217), not really suitable for the highway traffic volume. Consequently, the resulting extra travel time to cross the Oude Maas River could run up to 30 or even 60 min during peak periods, introducing high economic/societal cost.

The Heinenoord Tunnel has a length of 614 m [3]. The total length of the structure (tunnel including ramps) is 1,064 m. The tunnel consists of two unidirectional tubes, one for each direction. Each tube has three lanes. Each tube is equipped with, among other things, longitudinal ventilation, CCTV, various detection systems, a PA-system and emergency exits. Moreover, the tunnel is fully operated from a regional traffic centre.

It is a submerged tunnel, consisting of five elements. The ramps and tunnel portals (including the service buildings, visible as yellow buildings on both sides of the river in Fig. 2) were constructed through cut and cover.

Fig. 1 Location of the Heinenoord Tunnel in The Netherlands.

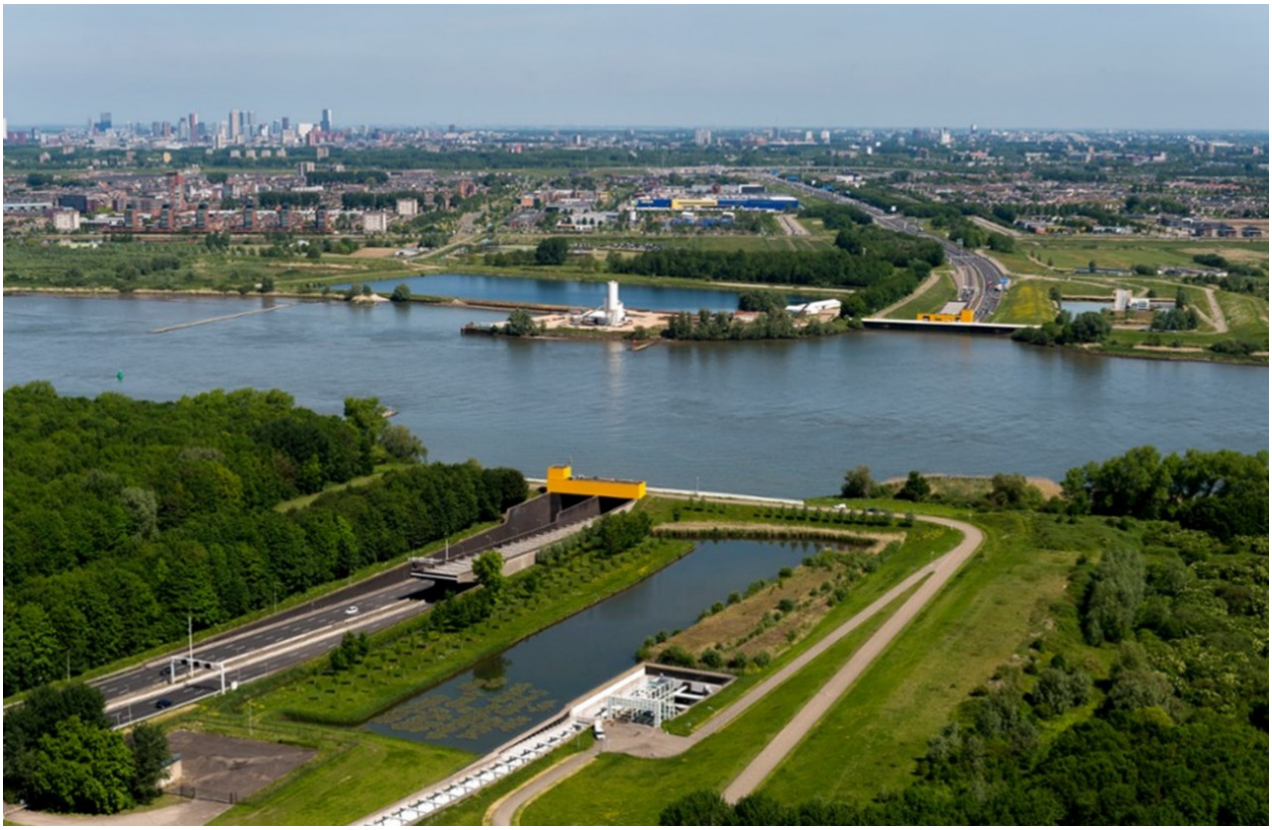

Fig. 2 Heinenoord Tunnel crossing the Oude Maas River; view to the north, showing the Rotterdam skyline on the horizon.

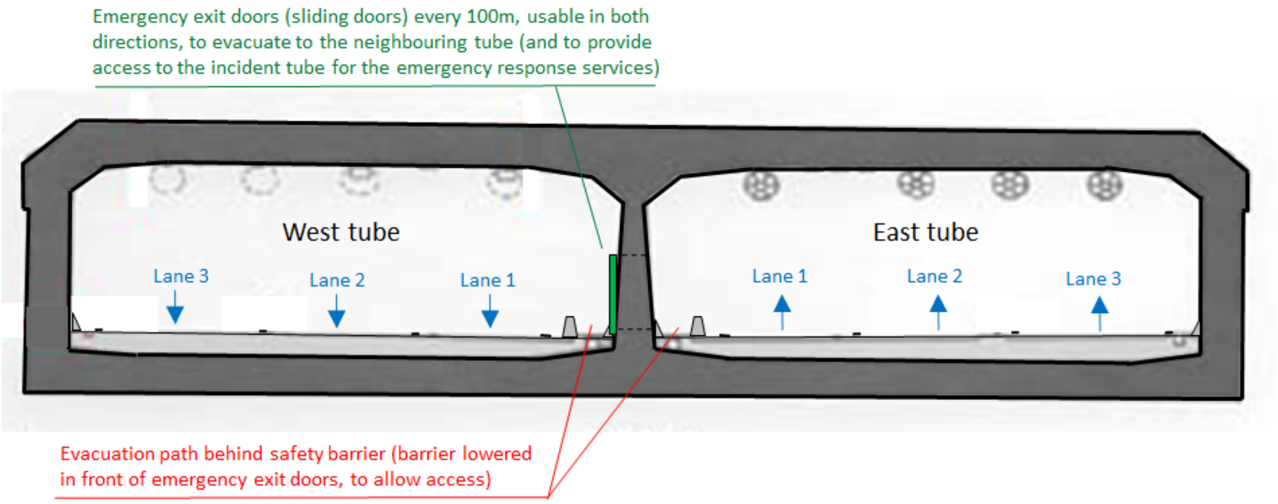

Fig. 3 Cross-section of the Heinenoord Tunnel in the current situation.

Currently, the tubes are separated by a single middle wall (see Fig. 3), whereas most tunnels in The Netherlands have a central gallery between the tubes, containing a separated emergency escape gallery and service gallery, for tunnel installations and cables. In the Heinenoord Tunnel, the escape route in case of emergency currently leads through the neighbouring tube, that is accessible through emergency exit doors in the middle wall. Moreover, the installations and cables that are normally in the service gallery, are currently located in the tunnel tubes, not accessible for maintenance without closing (at least two lanes of) the tunnel tube.

3. History

The tunnel was opened for traffic in 1969. The construction took about three years (excavation works started in 1966).

The tunnel is a replacement for the Barendrecht Bridge, a movable bridge that had to be opened regularly to allow shipping to pass, a feature not suitable for the growing traffic volume. Moreover, the bridge had become too narrow to handle the traffic volume in the first place. After the Heinenoord tunnel was opened, the bridge was demolished.

At first, because the Barendrecht Bridge was used by both highway traffic and slow traffic (pedestrians, cyclists, mopeds and tractors) the Heinenoord Tunnel had to service all these traffic categories. To provide for this accommodation, one lane in each tube was reserved for slow traffic and two lanes for highway traffic. However, after a few decades a subsequent capacity bottleneck appeared, because of the continuous growth of the highway traffic volume. As a temporary solution, the lane for slow traffic in the eastern tube was scrapped in 1991, providing an extra lane for the highway traffic. This meant that the lane for slow traffic in the western tube became bi-directional from then on.

The permanent solution consisted of the construction of a separate tunnel for slow traffic, the Second Heinenoord Tunnel. This tunnel, opened in 1999, was the first bored tunnel (using a Tunnel Boring Machine, TBM) in The Netherlands [4]. The Second Heinenoord Tunnel is 941 m long. It consists of two bores, with an outer diameter of 8.3 m. The width of the roadway is about 6 m in both bores. One bore is used by cyclists and pedestrians, the other bore by tractors (agricultural traffic) and mopeds. The traffic in both bores is bi-directional, although there is a traffic light system allowing the bore for agricultural traffic to be closed temporarily in one direction, to allow the passing of a tractor with a voluminous load from the other direction. The south entrance of the Second Heinenoord Tunnel is visible in Fig. 2, to the right of the Heinenoord Tunnel. The white-coloured ramp is used by the tractors and mopeds, the cyclists and pedestrians use an escalator as well as an elevator to enter the tunnel.

The construction of the Second Heinenoord Tunnel was a pilot project, to gain experience with the possibilities to use a TBM in soft soils, under high groundwater level circumstances. This experience was used later on for the construction of the second bored tunnel, the much larger and much more important Westerschelde Tunnel (opened in 2003) [4]. The Westerschelde Tunnel is the longest tunnel in The Netherlands (6.6 km).

4. Refurbishment

After more than 50 years of service, the structure of the Heinenoord Tunnel is still sound, apart from some relatively minor issues, but a full refurbishment of the installations and systems is required, because they are end of life. The refurbishment allows the tunnel system to be upgraded according to the RWS Tunnel Standard. However, even the current tunnel system complies with the legal safety requirements and works well in terms of availability for traffic. Moreover, the capability to deal with disruptive (traffic) events is on par with the RWS requirements. Therefore, no specific objectives were set to improve resilience, beside the main goal to organize the refurbishment itself (as well as future maintenance works) in a resilient way, to limit the nuisance for traffic as much as possible.

A long closure of the tunnel (or even one tube) to carry out the refurbishment is not possible, because alternative routes are scarce and require significant extra travel time, not suitable for the high traffic load. Thus, various scenarios were considered to assure the accessibility of the Hoeksche Waard during the refurbishment works, scheduled for 2023-2024. Multi-criteria analyses were performed for each scenario, mainly taking into account the total project cost, total societal cost (due to extra travel time during the refurbishment) and the total required time span for the works (calendar time).

In the end, refurbishment through "parallel assembly" [5] proved to be optimal. This concept means that the new installations and systems are installed next to the current ones, that will remain in service until the end phase of the refurbishment. The existing installations and systems are only dismantled after integral testing has shown that the completed new ones work properly. This approach allows most of the works to be carried out during a series of night and weekend closures of just one tube. This limits nuisance, because each time one driving direction is left undisturbed, while the nuisance for the other driving direction (extra travel time connected due to the alternative route) is limited because the closures take place in low-traffic periods. Before reopening the tunnel tube after a night or weekend closure, a series of simple regression tests are performed (see Section 6) to demonstrate the current installations and safety systems have not been compromised by the refurbishment works and still function properly.

To facilitate the parallel assembly, and to create better evacuation facilities for the future, a central gallery (consisting of an escape gallery and a service gallery) will be constructed in the west tube, during one of the first phases of the refurbishment. The width of the cross-section allows for this, because in the current situation there is an evacuation path behind the safety barrier on the left side of the roadway in both tubes (see Figs. 3 and 4).

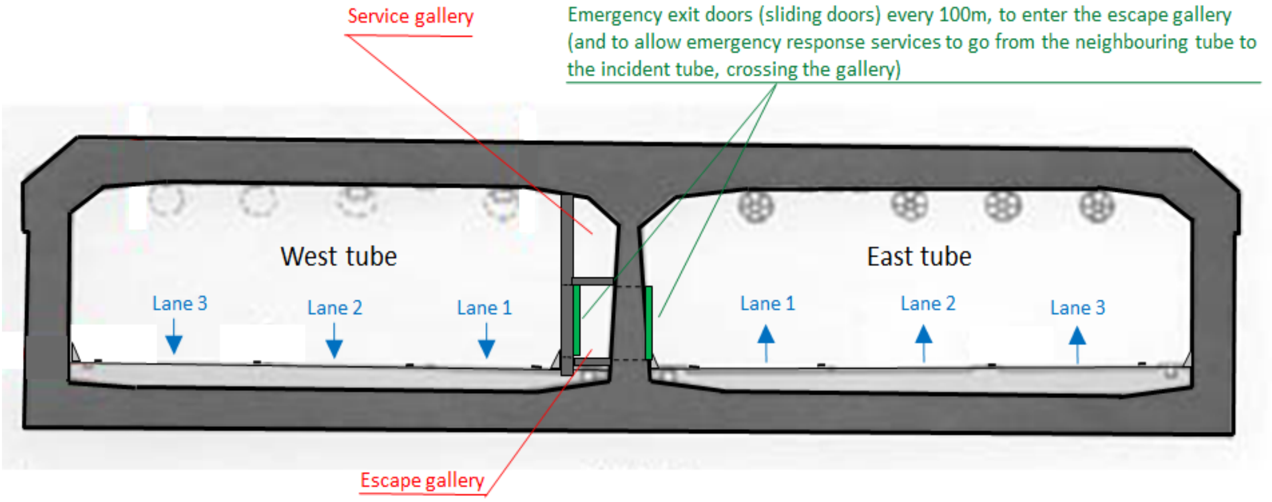

Fig. 4 Cross-section of the Heinenoord Tunnel in the future situation, after the refurbishment, including a central gallery (escape gallery and service gallery).

The rationale for this approach is that, as research shows, normally 50% of the tunnel installations are located in the service buildings, 40% in the service gallery and only 10% in the tunnel tubes [5]. This means that, when a central gallery is present, most of the parallel assembly works can take place outside the night and weekend closures, while the tunnel tubes are still in service for traffic (provided the escape gallery remains available for possible evacuation situations, which is normally the case, since the service gallery is in a different compartment).

Moreover, a central gallery will enhance the possibilities for future maintenance and refurbishments without the necessity to close a tunnel tube, thus enhancing the resilience of the tunnel system.

The disadvantage of constructing a central gallery is that the tunnel has to be fully closed for a certain time period, because both tubes are needed as a site to facilitate the works and the accompanied logistics. However, using prefab components and an “industrial” construction process (validated by practicing in a mock-up tunnel resembling the actual situation) the main structure of the gallery can be finished in two calendar weeks, scheduled in the summer holiday period of 2023. In this period, the traffic load is somewhat lower compared to normal working days (and maybe the habit of working at home more often, introduced by the COVID-19 pandemic, will also help in this case). This two-week closure will therefore produce less nuisance than the total nuisance that would follow from additional night and weekend closures that would be required without constructing a central gallery.

A second two-week full closure of the tunnel will be required in the end phase of the refurbishment, for integral testing of the new installations and systems and for training of the tunnel staff (including operators) and emergency response services. This second full closure is also scheduled in a summer holiday period (in 2024).

To summarize, the total number of closures to facilitate the refurbishment is as follows:

- 30 weekend closures and 40 night closures of one tube;
- Two periods of two weeks (and one extra weekend) in which the tunnel is fully closed (both tubes) in the summer of 2023 and 2024 respectively.

To mitigate nuisance for the traffic, public transport is promoted by running extra bus services during closures. In combination with this, the detour route for busses is shortened by temporarily allowing them to pass through the bore of the Second Heinenoord Tunnel that is normally used by tractors and mopeds. To make this possible, several temporary extra safety measures have to be implemented (see Section 7). Since the detour route for the other traffic through the Kil Tunnel is significantly longer, it is expected that, during refurbishment closures, many people will choose to travel by bus rather than by car.

A schematic overview of the refurbishment phases and scope is presented in Fig. 5 (part of an infographic for the public). In addition, Fig. 7 shows an artist impression of the end result of the refurbishment.

5. Selection of Refurbishment Approach (in Search of Resilience)

The main objective ("mission") was to find an approach for the refurbishment works that balances safety, nuisance for traffic (accessibility of regional destinations), technical feasibility and project cost, see Fig. 6.

Various scenarios for the execution of the refurbishment works were considered and evaluated in order to select the optimal solution to be implemented in the contract. This approach was "holistic", and could be tackled from various angles, but basically, the starting point was to consider a certain scenario, like closing one tube for refurbishment while temporarily allowing bidirectional traffic in the other tube. Then, for that concept, the required measures to assure traffic safety, tunnel safety and the occupational safety for the construction workers were defined. Subsequently, the consequences for the accessibility (traffic flow) were

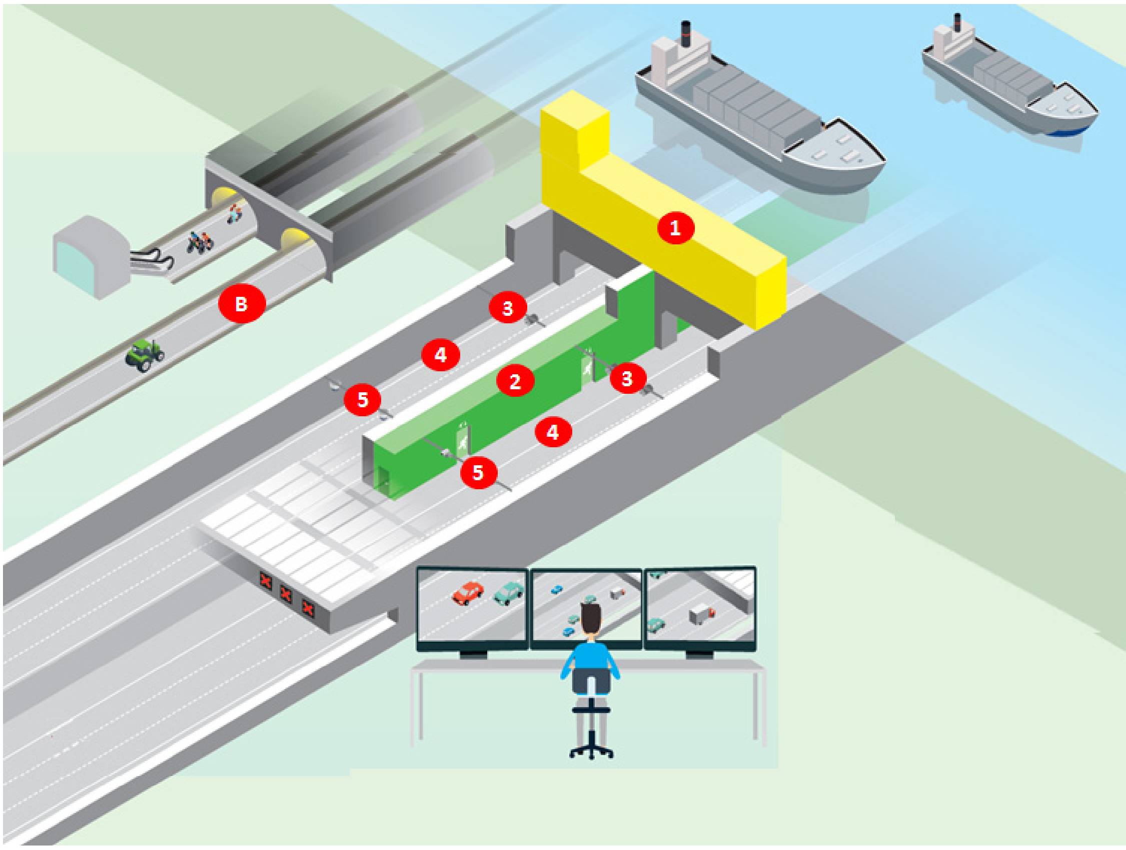

Fig. 5 Infographic on the refurbishment of the Heinenoord Tunnel.
B = temporary bus transport through tube of Second Heinenoord Tunnel (normally used by tractors and mopeds);
Refurbishment phases:
1 = Refurbishment service building; civil works: 10-weekend closures and 10-night closures of 1 tube;
2 = Construction of central gallery (escape gallery and service gallery): full closure both tubes during 2 weeks + 1 weekend;
3 = Installation works in tunnel and service gallery: 15 weekend closures and 30-night closures of 1 tube;
4 = Switching from old to new installations (including testing and training): full closure both tubes during 2 weeks;
5 = Removing old installations: 5-weekend closures of 1 tube.

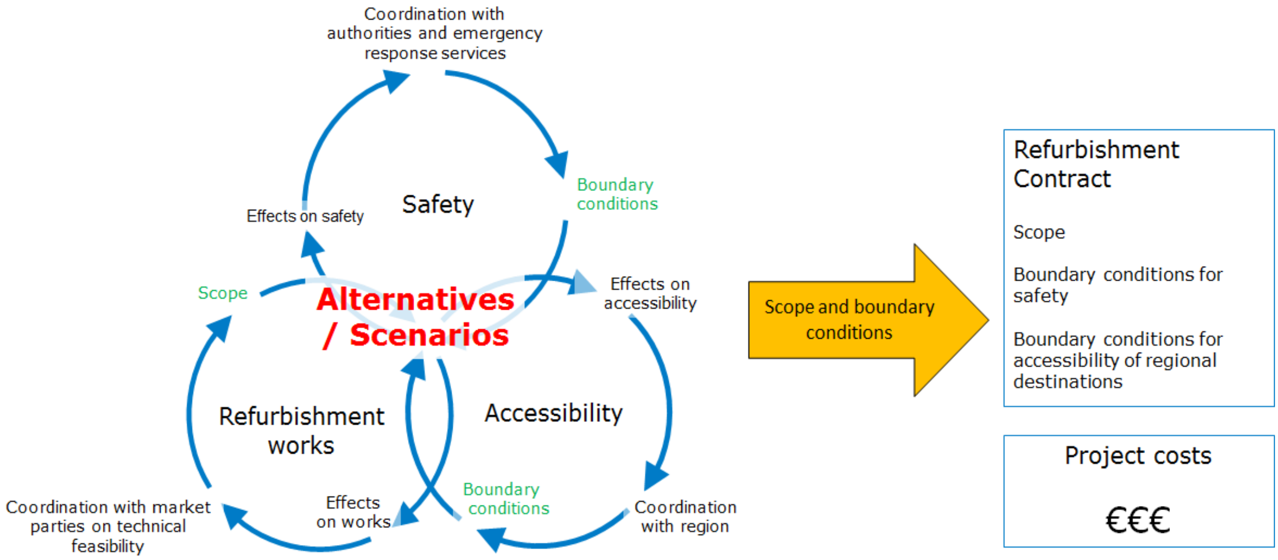

Fig. 6 Balancing possibilities for refurbishment works, safety, accessibility and project cost.

Fig. 7 Artist impression of the Heinenoord Tunnel after the refurbishment (Syb van Breda & Co Architects), view of the south portal; the green door between the tubes is one of the two exits of the escape gallery (the other one is at the north portal).

determined, as well as the possibilities to execute the works effectively and efficiently within these boundary conditions. Based on these analyses, the total project cost, total nuisance for the traffic and the required time schedule/lead time for the scenario could be determined.

By analysing all relevant scenarios along this way, the optimal solution, as mentioned above, could be selected, by applying a multi-criteria analysis. The following criteria, related to the aspects presented in Fig. 6, were taken into account:

(1) Technical impact

- Scope of the works that can be included in the refurbishment (given the scenario);
- Possible technical issues, uncertainties or risks;
- Expected life span of the results, before a next refurbishment would be required (goal: structure 30 years and installations/systems 15 years).

(2) Accessibility/nuisance for traffic

- Total travel time delay (per trip during rush hour) due to detour and/or congestion;
- Total duration of the nuisance during the period of refurbishment;
- Required measures (infrastructure, mobility, communication) to assure or improve accessibility;
- Direct societal/economic damage (monetized in euro) caused by loss of time/travel time delay during the total period of refurbishment; the monetized damage is based on validated cost of loss of time, taking into account the shares of business traffic, freight traffic and private/social traffic; the loss of time is determined on the basis of traffic flow models;
- Expected cost of compensation for freight transporters (to be paid by the ministry); this cost obviously is related to the calculated economic damage mentioned above;
- Effects on image (public opinion);
- Possible effects on motivation of traffic participants to travel outside peak hours;
- Required communication to the public.

(3) Project cost

- Total expected costs (in millions of euro's);
- Possible additional cost, due to risks.

(4) Safety and sustainability

- Main points of attention to assure safety (cost of required safety measures already included in total project costs as mentioned above);
- Main points of attention to assure sustainability.

(5) Summary of opportunities and threats

- Opportunities;
- Threats;
- Further required studies.

In the above list, accessibility (limitation of nuisance for traffic) is a very important criterion, more so than project cost, although, of course, the required budget had to be feasible within a certain acceptable range.

The main challenge in the process was to find or create possibilities to perform the refurbishment works, while maintaining an acceptable travel time for the traffic, under acceptable safety conditions. In general, more (safe) availability for traffic means fewer possibilities to perform the work, resulting in a longer period in which the refurbishment takes place. Thus, balancing the degree of nuisance and the duration of nuisance, two important resilience aspects, was also important. That is why the total monetized economic damage, based on the total loss of time (travel time delay) during the refurbishment period, was chosen as a fitting criterion.

The following scenarios were considered:

(1) Limit the refurbishment scope to the most urgent installations and systems: no civil works and some installations not yet completely end of life remain in service, resulting in an additional refurbishment later on;

(2) Parallel assembly during weekend and night closures (the chosen alternative);

(3) Same as 2, but only night closures (resulting in a longer time span for the refurbishment, because the performance of the works is less efficient);

(4) Closure of one tube at the time for refurbishment and allowing bi-directional traffic in the other tube (without allowing trucks and dangerous goods that could cause a large fire, because the longitudinal ventilation is not fit for bi-directional traffic);

(5) Same as 4, but not a full closure of a tube, leaving one lane available for traffic (requiring safety measures for the construction workers and severely limiting the efficiency of the works, resulting in a long required time span for the refurbishment and nuisance);

(6) Construction of a temporary bridge to cross the river (in one or two directions) and then close a tunnel tube or the entire tunnel for refurbishment;

(7) Same as 6, but construction of a new tunnel (one or two tubes) instead of a temporary bridge.

The multi-criteria analyses showed that scenario 1 would not meet the goals for the life span of the tunnel system. Scenario 3 would be less effective than scenario 2 and scenarios 4 and 5 would cause heavy congestions on weekdays that are not acceptable. Scenario 6 proved to be technically difficult, because of the required height of the bridge and/or required bridge openings during peak hours (to let tall sea-going vessels pass).

Scenario 7 would be (too) expensive and the required time span to finish the refurbishment would be too long (also considering the risks connected to the fact that the tunnel systems are end of life). Scenario 2 proved to be best for accessibility/availability, and also positive for the total project cost.

6. Safety Aspects

Since the selected approach implies that the tunnel still will be used by traffic during the refurbishment period, special attention is to be given to the safety of both the road users and construction workers. Safety is also a mandatory constraint for resilience, see the definition in Section 1 [1].

As a starting point, the following characteristics of the approach contribute to safety:

- The new facilities (installations and systems) will be mounted next to the existing ones (parallel assembly); the existing facilities will remain in function until the new ones are fully completed and demonstrably functioning properly. Only then, the existing facilities will be dismantled.
- When work is being carried out in a tube, it is generally closed for traffic.
- For this reason, work in a tube takes place at low traffic times as much as possible, during weekend and night closures. Two periods of two weeks (during low-traffic summer holiday seasons) have been reserved for the more time-consuming activities, during which the entire tunnel (both tubes) will be closed.
- During closures of tubes, measures are taken to guarantee accessibility in the region as much as possible (to avoid the creation of dangerous traffic situations elsewhere).
- As far as possible, work installations and systems outside the tunnel tubes (e.g. in the service gallery or the service building) can also be carried out while the tunnel is open for traffic, provided that the functioning of the existing facilities (which are still operational to ensure safety) is not hindered.

In line with these characteristics, the following safety boundary conditions are included in the refurbishment contract:

- During the refurbishment, the adequate functioning of the operational safety facilities (installations and systems) must be guaranteed. This not only means that adequate conservation and maintenance is required (including inspections and tests), but also that the newly installed facilities must not hinder the functioning of the existing ones (e.g. a new camera should not block the air flow from an existing ventilation unit and a new ventilation unit should not block the view of an existing camera).
- When an operational facility fails, it must be repaired in accordance with the recovery priorities of failure definitions of the RWS Tunnel Standard, taking into account the compensatory measures that are normally implemented until the repair is finished, in accordance with the current Safety Management Plan for the Heinenoord Tunnel.
- The work may not affect the functioning of the facilities that play a role in guaranteeing tunnel safety for those present in the tubes that are fully or partially open for traffic at that time. In addition, it is not permitted to temporarily take these facilities out of use. Taking temporary measures to safeguard the continuity of functioning during the work is permitted. If it is not possible to prevent the functioning of the facilities from being disrupted during the work, the entire tunnel must be closed for the purpose of carrying out the work in question.

- When working in a tube, it must be completely closed for traffic, with the following exceptions:

(1) Emergency response services may use the closed tube for passage in case of emergency. The work must be arranged in such a way that this is possible in a safe way. Moreover, in the event of a disaster in the tube that is still open for traffic, the emergency response services must at all times be able to use the neighbouring work tube as a support tube when dealing with the disaster (e.g. to approach the disaster location in the traffic tube through the emergency exit doors).

(2) During the phases in which the entire tunnel is closed for traffic (phase 2 and phase 4), bus traffic with a frequency according to the current timetable must be allowed to pass through one of the traffic tubes, in a driving direction to be determined. The work must be arranged in such a way that this is possible in a safe way (bus traffic in the opposite direction will be guided through the Second Heinenoord Tunnel).

- Before a tube is reopened for traffic after work in the tube in question, it must be demonstrated that the existing facilities are still working properly. This regression tests must include at least:

(1) Emergency test: activate the emergency button in the traffic control centre and verify that all actions associated with this command are performed correctly (like activation of the tunnel ventilation and closure of the tunnel);

(2) Evacuation test: activate the evacuation button in the traffic control centre and verify that all actions associated with this command are performed correctly (like activation of the evacuation lighting, evacuation messages through the PA-system and activation of the sound beacons above the emergency exit doors);

(3) Sensor test: verify that (a representative sample of) the sensors in the tunnel (SOS, emergency telephones, smoke detectors and sensors that indicate the use of emergency aid cabinets, etc.) work correctly, including all actions that should follow a detection (e.g. automatic activation of the tunnel ventilation). In addition, the emergency telephones should establish an automatic connection with the operator when the receiver is picked up.

- It is not permitted at any time during the refurbishment to set up bi-directional traffic in one tube.
- If one or more tubes are (partially) open for traffic, neither the escape routes nor the approach routes for the emergency response services may be blocked by the work. The accessibility of the emergency aid cabinets may not be blocked either. Exception: if it can be assured that a blockade of a route can and will be lifted within 2 min after an emergency alarm by the tunnel operator, this precondition is considered to be met as well.

Very much related to these boundary conditions to assure safety, intensive coordination was required with the local authority (municipality) that is responsible for issuing the building permit and the permit for the re-opening of the tunnel after refurbishment, to align the phases of the works with legal decision-making process and the legally required facilities when a tunnel is in operation. The chosen concept of parallel assembly helped in this context, because it is transparent that current safety systems remain in service until the very end of the refurbishment.

Fig. 8 In May 2022, the bore of the Second Heinenoord Tunnel for tractors and mopeds is closed for the assembly of temporary technical measures to facilitate public transport (busses) during the refurbishment period (picture by Robin Witkamp, RWS).

7. Mitigating Measures

Various measures are being prepared and implemented to mitigate the nuisance that will occur for the traffic, despite the "public-friendly" refurbishment approach described above.

First of all, an information campaign is running, about the scope and the schedule of the works. The dates for the tube and tunnel closures in 2023 and 2024 are already set and included in the communication, involving newspapers, websites and local radio and television. Although the full tunnel closures will be limited to two times two weeks in the relatively traffic-low summer holiday seasons, it is expected that these closures will cause the most nuisance. The campaign is aimed to prepare the public to, for example, plan their holiday during those periods, or to work at home, or to use alternative transport means, like the bus, train, bicycle or moped.

For the local people who are still dependent on their car, the designated alternative route to and from Rotterdam will run via the Kil Tunnel (part of the secondary road N217) and the A16 highway. Therefore, the traffic flow on the N217 will be optimized by increasing the capacity of a roundabout that will otherwise form a bottleneck.

It is expected that the through-traffic from outside the Hoeksche Waard will also use the A16 instead of the A29. Therefore, the emergency lane of the carriageways for both directions will locally and temporarily be used as extra driving lane, combined with a reduction of the speed limit for reasons of both safety and traffic flow.

Public transport is promoted by running extra bus services during tube or tunnel closures. As already mentioned in Section 4, busses will be allowed to temporarily pass through the bore of the Second Heinenoord Tunnel that is normally used by tractors and mopeds. To make this possible, several temporary extra safety measures are being implemented, in intensive coordination with the local authority and the local fire brigades. This has to do with the fact that there are no emergency exit doors present in the Second Heinenoord Tunnel (there are no cross connections between the bores). Moreover, the tunnel ventilation is only suitable for air exchange, not for smoke control in case of fire. This is acceptable for the normal traffic, occasional tractors and mopeds with one driver, but for busses with lots of people on board a complete new safety concept had to be developed to compensate for the lack of emergency exits: "back to the drawing board" to re-invent safety from scratch, relying more heavily on operational measures.

The solution was found by installing temporary longitudinal ventilation units (jet fans) at one of the portals (see Fig. 9) with enough capacity to control bus fires (20-50 MW). When busses go through the bore the ventilation is permanently fully activated, a preventive measure to maximise effectiveness in case of fire. In addition, on-site traffic officers control the arriving busses (traffic metering) in a way that only one bus at the time is present in the tunnel: the next bus is only allowed to enter when the previous bus has left the tunnel. That way, in case of fire, people from the bus can evacuate smoke free by walking out of the tunnel in the direction opposite of the direction of ventilation. The ventilation direction is always to the north, making use of the dominant wind direction. This means that the evacuation direction is always towards the south portal. The bus drivers are instructed to guide this evacuation, supported by a steward (emergency response officer) that is also present on every bus. Lastly, a quick response fire-fighting team is present on site. This concept allows a bus to pass every 2 min. The timetable for the bus service is organised on this basis.

During a certain day's service, busses will only go through the bore in one direction. This adds to the robustness of the concept. Busses in the opposite direction will use the tunnel tube of the Heinenoord Tunnel that is still available for traffic. In the periods of full closure of the tunnel (works going on in both tubes) the busses in the opposite direction will still be allowed to pass through one allocated (most suitable) tube; the works have to be organised in such a way that is safely possible.

Moreover, during the days that the Second Heinenoord Tunnel is used by busses, the bore in question is closed for the normal traffic (tractors and mopeds). The mopeds are then allowed to use the bore for cyclists and pedestrians. The tractors have to wait until the bus service of the day has ended. However, the bus service will be interrupted when the emergency response services have to use the bore for a priority ride (use of the bore to reach a calamity location on the other side of the river). All these principles underline that the traffic management by the on-site traffic officers is a crucial part of the safety concept.

Additional temporary measures to support the safety concept involve an extra fire extinguishing installation (water pipe) for the quick response fire-fighting team and evacuation lights and signing to guide people out of the bore in the very-low-probability case that the ventilation malfunctions at the exact moment of a fire (see Fig. 10). Moreover, to support the operational procedures, an intensive tailor-made training programme is implemented for all the involved personnel, validated by a full exercise. Finally yet importantly, the effectiveness of the operational measures will be monitored and evaluated on a daily basis, resulting in improvement measures when necessary.

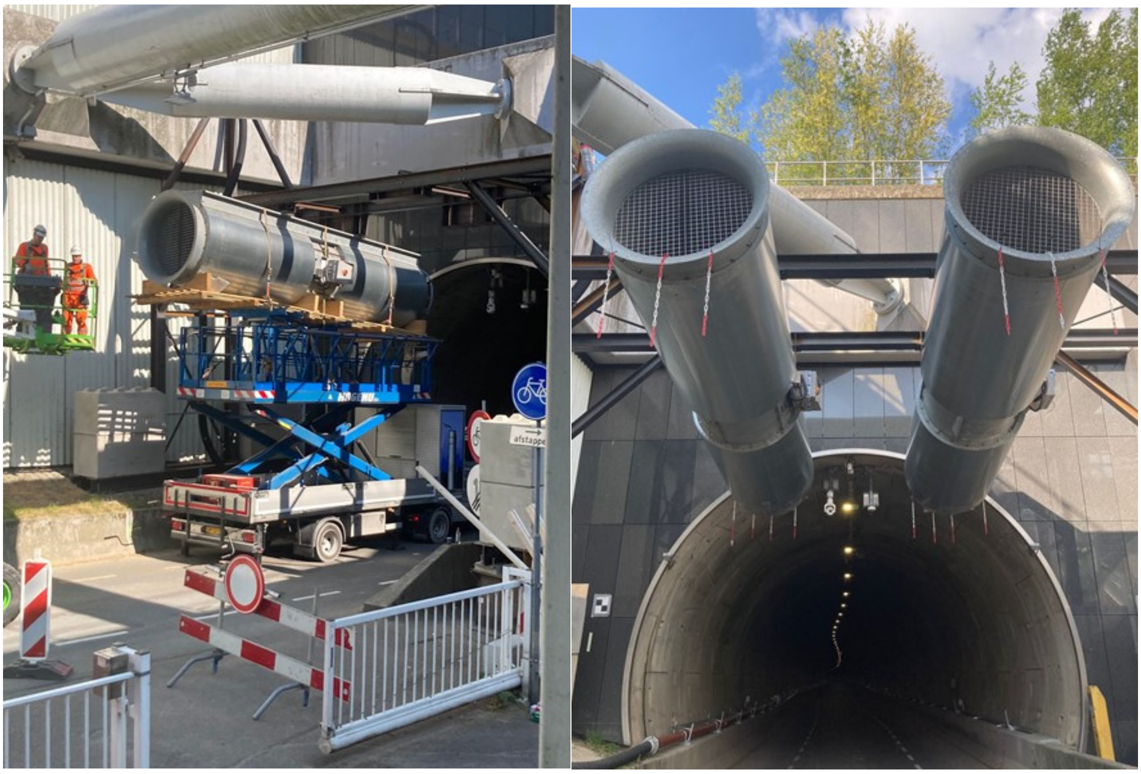

Fig. 9 In May 2022, the temporary extra jet fans to support public transport (busses) through the Second Heinenoord Tunnel are being mounted (pictures by Robin Witkamp, RWS).

Fig. 10 In May 2022, the temporary evacuation lighting and fire extinguishing installation to support public transport (busses) through the Second Heinenoord Tunnel are being mounted (pictures by Robin Witkamp, RWS).

The assembly of the temporary technical measures in the Second Heinenoord Tunnel has already started in May 2022 (see Figs. 8-10) because the availability of the bore for busses is an important constraint to start the “real” refurbishment works.

8. Conclusion

It is not possible yet to evaluate the refurbishment approach itself, because only a few preparatory works have been carried out at the moment (May 2022). However, the process to select the approach has been proven very useful. It has provided crucial insights into the different impacts of the works and has served as a basis for coordination and communication with the numerous stakeholders in the region. This has created support for the measures. In addition, it provides a blueprint or pilot for the preparation of a larger tunnel refurbishment programme that is scheduled after the Heinenoord Tunnel.

From a resilience point of view, two aspects prove to be relevant:

- The inventory of the resilience of the current tunnel system, of which the tunnel manager may not be (fully) aware in advance: what possibilities does the current tunnel system offer to reduce nuisance in case of maintenance or refurbishment? The findings of this inventory ought to be documented in the maintenance plan for the tunnel;
- Possibilities/provisions, to be included in the refurbishment scope, to enhance the resilience for future maintenance and refurbishment works (like, in this case, a service gallery).

In addition, we became even more aware that standardized modules for tunnel installations and systems are very beneficial for reducing the required time to replace existing end-of-life installations during a refurbishment. Thus, standardized modules support the reduction of nuisance for the traffic. This will be taken into account when preparing the subsequent refurbishment programme for other tunnels.

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