Widening the "Montedomini" tunnel in the presence of traffic: the evolution of the "Nazzano" method.

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ABSTRACT: Widening a motorway tunnel in the presence of traffic without resorting to alternative routes or reductions in the level of service was attempted for the first time in the world in the early 2000's to widen the Nazzano Tunnel (A1 Motorway , near Rome). Completion of that project constituted without doubt a true milestone for tunnelling. It demonstrated the feasibility and efficiency of the method, which by reducing land consumption to a minimum, made it possible to expand the capacity of strategic road, motorway or rail infrastructures without reducing the level of service during construction operations. The solution to widen the existing tunnel without interrupting traffic had now become a reliable and advantageous option for clients where possible alternatives (driving a third tunnel or closing traffic in the carriageway to be widened) can be more financially and socially costly than widening the existing tunnel.

1 INTRODUCTION

Until just a few years ago, when a road tunnel consisting of two bores side-by-side needed to be enlarged while maintaining the tunnel in service, either a new bore was driven beforehand through which traffic was deviated or one of the two bores of the tunnel was closed, thereby reducing the level of service to users as a consequence.

A technique conceived of by the author was developed in Italy at the beginning of the 2000's on the Nazzano motorway tunnel. It enables a road, motorway, rail or metro tunnel to be widened without halting traffic and therefore without substantially affecting the level of service provided by the infrastructure and without the need for resort to expensive alternative routes through new bores, whether final or temporary, which moreover are not always feasible due to the lack of the necessary space.

After a brief description of the procedures employed in the first experimentation in the world of the method used to widen the Nazzano Tunnel without halting traffic, an analysis is given below of the data acquired during the first experimentation. An illustration is then given of the improvements, modifications and developments which were implemented in the second experimentation to widen a tunnel in the presence of traffic, which is currently in progress on the Montedomini tunnel (A14 motorway).

2 THE MAIN ASPECTS OF THE "NAZZANO METHOD"

The first step to be taken when widening a tunnel while it is in service is to identify a system designed to guarantee total safety for the users, who to all intents and purposes pass through a complex construction site for an underground project. At the same time a construction system must be devised which will allow the necessary work to be carried out in very small spaces, because the space in the centre of the tunnel is used for traffic flow.

The safety of users can be achieved by installing a special shield designed to physically separate construction areas in the tunnel from those used for traffic flow.

The solution devised at Nazzano to perform this function was a "tunnel widening traffic protection shield" or "counter tunnel" made of steel, which separates the construction site area from the motorway.

The protection in question must satisfy the following requirements:

- resistance to shocks from excavated material or from ill-fated collapses, which might fall on the protection itself;

- its dimensions must be compatible with the transit of vehicles inside it and with the dimensions of the tunnel to be enlarged. In consideration of the dimensions and the characteristics of the Nazzano tunnel, the shield employed allowed traffic to transit on two lanes, a 3.50 m lane for heavy traffic and a 3.00 m overtaking lane for lighter vehicles;

- resistance to potential impacts from vehicles in transit.

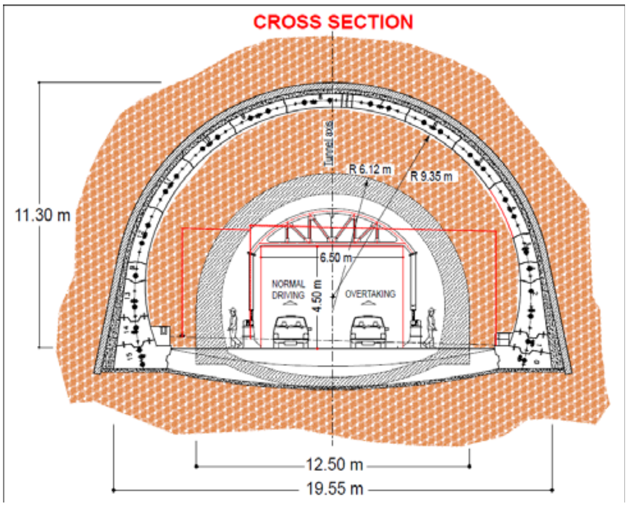

Figure 1. Nazzano Tunnel: tunnel section type for widening in the presence of traffic

Generally, a shield of this type must be either in steel, shorter in length than the tunnel, self-propelled and positioned continuously astride the face, as it was at Nazzano, or in reinforced concrete, longer than the tunnel and immobile.

The presence of a traffic protection shield has an appreciable effect on the working areas used to widen the tunnel and it also affects the choice of the type of construction significantly. Standard tunnel advance, which involves placing a preliminary lining consisting of steel ribs and shotcrete and casting the final lining in situ at a certain distance from the face using tunnel shuttering would be basically incompatible with the space available.

Two types of technology were therefore chosen for the preliminary and the final linings that could be adapted to the construction site layout as constrained by the presence of a traffic protection shield.

The technology chosen for the preliminary lining was that of mechanical precutting, which consists of making an incision in the face of appropriate thickness and length around the extrados of the tunnel to be excavated, which is immediately filled with fibre reinforced concrete. A shell with a truncated cone shape is thereby created and tunnel advance takes place beneath it. In the case of Nazzano, the precut was made using a machine that was self-propelled and operated entirely above the traffic protection shield.

The technology chosen for the construction of the final lining, on the other hand, was that known as the "Active Arch" technique, which consists of erecting an arch of prefabricated concrete segments below the intrados of the precut shell. This arch is then immediately rendered self-supporting by the action of a flat jack fitted in the key segment.

This system enables a final lining to be installed at a very short distance from the face (3-6 m) extremely rapidly that is already self-supporting.

The erection of the prefabricated concrete segments can be performed as at Nazzano by making use of the same machine employed to carry out the mechanical pre-cutting, using the same supporting structure to handle, position and support the segments until the arch is put under pressure. This operation can also therefore be carried out without particular difficulty by working above the traffic protection shield in a manner that is fully compatible with the unusual layout typical of the construction site used to widen a tunnel in the presence of traffic.

Finally, the construction of the tunnel invert completes the tunnel widening operations. In cases of a twin bore tunnel, the tunnel invert can be constructed after widening both bores by channelling all the traffic through one bore while the tunnel invert is constructed in the other, which is closed to traffic. In cases of single bore tunnels or where the volumes of traffic are particularly large, the tunnel invert can be constructed in two stages: first along the whole of one side of the widened tunnel, maintaining traffic flow on the other half and then vice versa on the other side. In this case the two slabs will be connected by using appropriate sleeved reinforcements. Figure 1 illustrates the tunnel section type used for widening the tunnel while traffic is flowing employed at Nazzano, with the old tunnel in the centre and the traffic protection shield.

3 WIDENING IN THE PRESENCE OF TRAFFIC ON THE NAZZANO TUNNEL

3.1 *General details of the project*

The Nazzano Tunnel is twin bore, each approximately 337 m in length, and it is located on the A1 Milan-Naples motorway, approximately 40 km from Rome. The tunnel was widened from two to three lanes plus an emergency lane in each direction between 2004 and 2007. The client for the widening project was ASPI - Autostrade per l'Italia Spa. Rocksoil Spa was engaged for the design and for construction supervision, while the general contractor was Impresa COSSI Costruzioni Spa.

The area to be excavated inclusive of the tunnel invert but not including the existing tunnel was 158 m².

Today the tunnel, which has an inner radius of approximately 9.50 m, has four lanes, three for traffic and one for emergencies.

3.2 *The traffic protection system*

Figura 2 shows a photograph taken during operations to widen the old tunnel. The self-propelled traffic protection shield can be seen in the foreground mounted on prefabricated reinforced concrete components, fitted on the traffic side with a special profile similar to that of a "New-Jersey" safety barrier.

The central 20 m of the shield, which was 60 m in length, was appropriately reinforced on the inside.

As the tunnel face advanced, the shield was systematically moved forwards by special pistons in order to ensure that the reinforced part of the shield was maintained at the face.

Figura 2. Nazzano Tunnel: traffic protected by the steel protection shield while the old tunnel is being widened.

3.3 *The advance production cycle in the tunnel*

The Nazzano Method consists of a sequence of operating stages which, when repeated in a precise order, determine the tunnel advance production cycle.

The stages and the sequence of them, as carried out to widen the Nazzano tunnel, are summarised in Figure 3. It can be seen that each cycle is comprised of the execution of the precutting stage and four subsequent alternating stages of excavation and erecting the final lining of pre-fabricated concrete segments.

An advance cycle is 4 m in length and the distance between the face and the last arch of the lining erected varies between a maximum of 6.5 m and a minimum of 4.5 m.

As already mentioned, operations for precutting and the erection of the active arch final lining are carried out using a single machine, named a Multifunction Machine (M.M.), consisting of a robust dual arch steel structure (Figure 4).

A carriage is fitted on the first arch, which carries the cutter that makes the precut and the equipment used to fill it. The cutter is fitted with a toothed chain specially designed to break up the ground and remove it from the incision at the same time.

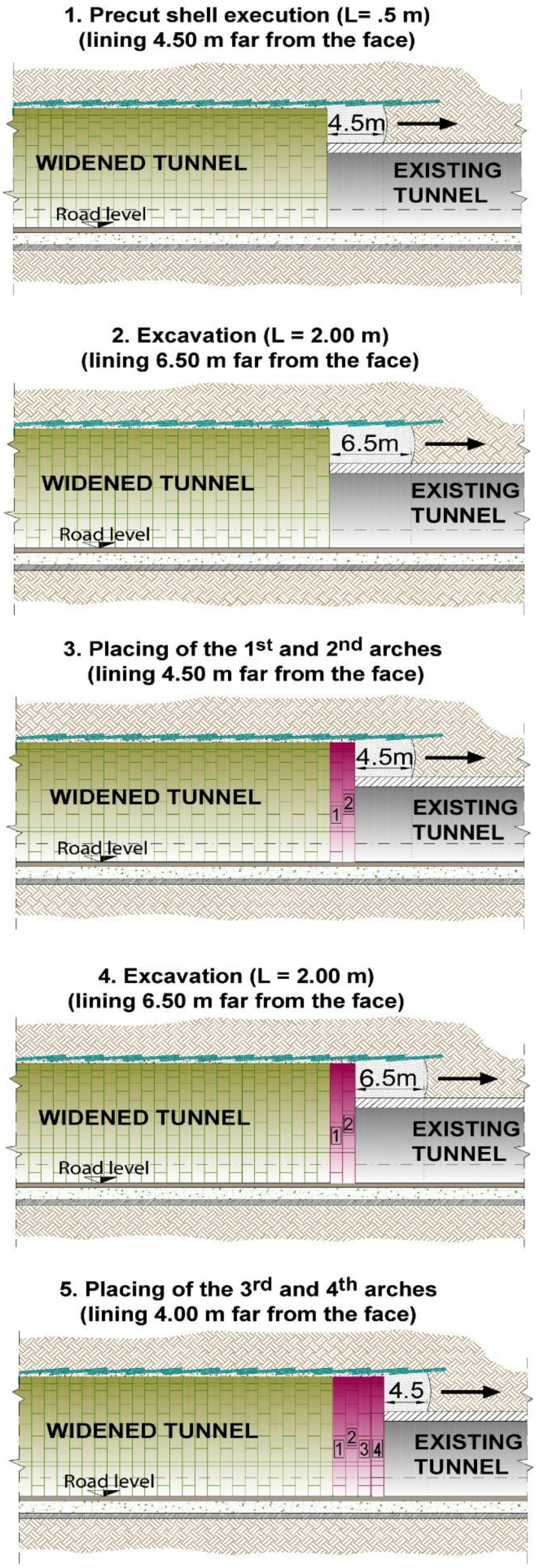

Figure 3. Nazzano tunnel: advance cycle

A carriage fitted with an "erector" runs on the rear arch, specially designed and dimensioned for placing the concrete segments of the lining. It "clips onto" the segments and positions them correctly in place. Special telescopic structures (retractable arms), anchored to the arch itself and fitted with sensors which enable all the essential manoeuvres to be carried out in safety, support the segments in the correct position for the whole of the time needed for the lining to become self-supporting.

The machine moves from the face to its resting position on top of a special transport shield which separates it from the traffic below while it is moving.

Figure 4. Nazzano tunnel: the Multifunction Machine

4 ANALYSIS OF PRODUCTION DATA ACQUIRED DURING THE WIDENING OF THE NAZZANO TUNNEL IN THE PRESENCE OF TRAFFIC

As already mentioned, widening a tunnel in the presence of traffic necessarily involves a construction site layout in which working spaces are very small and this puts substantial limits on the size of the equipment that can be used, which must nevertheless operate at considerable heights (10 m approx.).

Figure 5 shows the construction site layout employed for widening the Nazzano Tunnel in the presence of traffic.

The limits just mentioned obviously have strong repercussions on the maximum production rates that can be achieved during widening work.

The advance speeds achieved during widening of the two bores of the Nazzano Tunnel varied between 0.75 metres per day and 0.90 metres per day, with peaks very close to 1 metre per day (Figure 6).

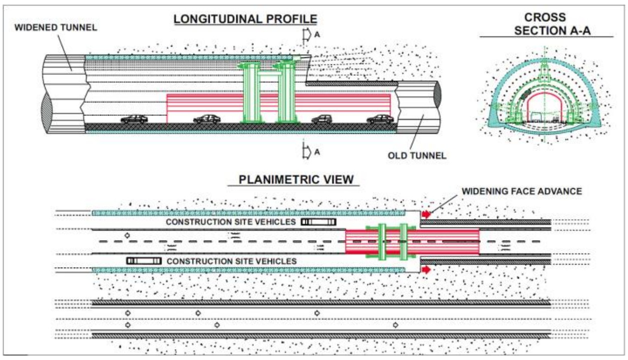

Figure 5. Nazzano Tunnel: lay-out of the construction site for tunnel widening in the presence of traffic

An analysis of the time taken for each stage of the advance cycle and its relative impact on production, together with an objective examination of the operating procedures adopted at Nazzano, generated some extremely useful ideas for improving and optimising the method.

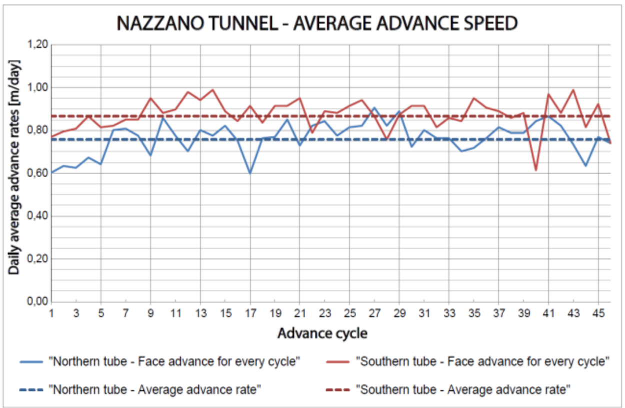

Figure 6. Nazzano tunnel: advance speeds for the widening face (showing the progress of the widened tunnel with the final lining already in place)

More specifically, production data was analysed, divided into macro-work stages, for a significant number of advance production cycles. By measuring the duration of each operating activity, its length as an average percentage of the advance cycle was calculated.

Each stage was therefore calculated as a percentage of the entire advance cycle and its impact on production was seen as a consequence.

Table 1 gives a very brief summary of the results of the analysis. It allows those stages which had most impact on production and which if improved would increase advanced speeds significantly to be easily identified.

More specifically it can be seen that the macro-work stage which had most impact on the length of the cycle is that for the erection of the "Active Arch" final lining, accounting for close to 50% of production.

Table 1. Percentage distribution of time taken for the precutting, excavation and lining stages

OPERATIONAL STAGE	AVERAGE PERCENTAGE IMPACT
Mechanical precutting	22.0%
Excavation for tunnel advance	24.1%
Direction of the final lining	46.1%
Ancillary activities	7.8%

5 POSSIBILITIES FOR OPTIMISING AND INNOVATING THE METHOD NAZZANO

Once the experiment in the widening of a tunnel while traffic was flowing had been successfully concluded at Nazzano, a new stage of in-depth study began on the results, in order to improve and optimise the method as much possible in view of a possible new application.

The experience acquired at Nazzano highlighted various difficulties which required action to improve the method used and to achieve even more satisfactory production objectives for both the contractor and the client as follows:

- optimisation of the extremely small operating spaces available;
- improve the production performance of the active arch, final lining, erection stage;
- choice and optimisation of operations to be performed by dedicated machines.

With regard to the first point, because the space available between the face and the active arch, final lining cannot be increased, since the precut shell must be confined as quickly as possible by the lining, and because on the other hand it is not possible to indiscriminately increase the dimensions of the excavation area which have a direct and large impact on construction costs, it is therefore essential to find different ways of using the available space above the traffic protection shield. This can be transformed from a component of protection and safety to become a true and genuinely useful "construction site area" to feed working areas at the face (transport materials, remove spoil on conveyor belts, etc).

The passage of vehicles and materials along the passageways at the side of the shield, which because of their small dimensions carry a significant risk of collision between moving vehicles and construction workers, can be reduced to a minimum in this way. These passageways allow extremely small margins for manoeuvre and as a consequence slow production rates appreciably.

With regard to the second point (improve the production performance of the active arch, final lining, erection stage), the data given in the previous section shows beyond any doubt that an improvement in the production performance of the erection of the active arches would have substantial impacts on overall production performance.

While optimisation of the active arch erection stage must be sought right from the design stage, improvements to the other two stages (precutting and excavation) are to be sought mostly in the execution procedures and in the choice of new and better performing equipment.

Finally, with regard to the third point (choice and optimisation of operations to be performed by dedicated machines) great consideration was given above all to the possibility of employing the M.M. also for the excavation stage.

The advantage of this idea lies in the elimination of all the time taken to move or to park the M.M. and to construct the rails on which it actually moves, to give a theoretical reduction in the length of the advance cycle of approximately 10%.

There are, however, disadvantages connected with the presence of an M.M. at the face: reduction in the available space, above all for spoil removal operations, both during the precutting and the excavation stages, and also for the operations needed to prepare the surface onto which the final lining in prefabricated concrete segments is installed.

The choice will therefore be influenced by the results of a cost/benefit analysis in terms of production times, related to a reduction in the time taken as a result of not needing to move the M.M. and the relative ancillary activities compared with the longer execution times resulting from a further reduction in the space available at the face.

6 APPLICATION OF THE TUNNEL WIDENING METHOD IN THE PRESENCE OF TRAFFIC ON THE MONTEDOMINI TUNNEL

In view of the good results achieved with this first experiment, the client, Autostrade per l'Italia S.p.A., which had commissioned the widening of the Nazzano Tunnel in the presence of traffic, decided to use the same method to also widen the Montedomini Tunnel, as part of the project to modernise the A14 Bologna-Taranto motorway and provide a third lane plus an emergency lane in the section between Ancona North and Ancona South, currently in progress.

For this new work, the contract for design and construction supervision was awarded to SPEA INGEGNERIA EUROPEA Spa and to ROCKSOIL Spa, while the construction work was awarded to GHELLA Spa.

6.1 *The Montedomini tunnel*

The twin bore Montedomini Tunnel is approximately 280 m long and currently houses two 3.75 m lanes on each carriageway. The project in progress consists of widening it to three 3.75 m lanes plus one 3.00 m emergency lane for each carriageway.

Section of tunnel which will be widened using the Nazzano method is 217 m in length. The remaining sections at the portals will in fact be transformed from ordinary underground tunnels into artificial tunnels.

As opposed to the Nazzano tunnel, which passes through sandy ground, the Montedomini Tunnel lies in clayey ground. The risk of encountering gas during excavation is very low.

The overburden varies from just a few metres to a maximum of 25 m. The area to be excavated inclusive of the tunnel invert but not including the existing tunnel is 211 m².

6.2 *Evolution of the method and differences from the Nazzano Tunnel*

Some modifications were made to the procedures for widening operations on the basis of the Nazzano experience. These modifications were made for two main reasons. The first regards the larger dimensions of the excavation area and the different geotechnical conditions of the context, with the presence of clayey rather than sandy ground. The second regards the improvements and optimisations to the construction system made on the basis of the studies and analyses described in the previous section with regard to improvements to the construction site layout at the various construction stages.

The larger dimensions of the excavation and the different geotechnical conditions made it necessary to employ a larger precut: 50 cm thick instead of 30 cm and 6 m in length instead of 5.5 m. The overlap between precut shells increased as a consequence from 1.5 m to 2 m.

The dimensions of the prefabricated concrete segments of the active arch, final lining also increased (from 2.2 m to 2.8 m thick at the base and from 60 cm to 70 cm thick in the crown) and as a consequence of the larger dimensions their maximum weight also increased to 80 kN.

Figure 7 summarises the differences between the two tunnels.

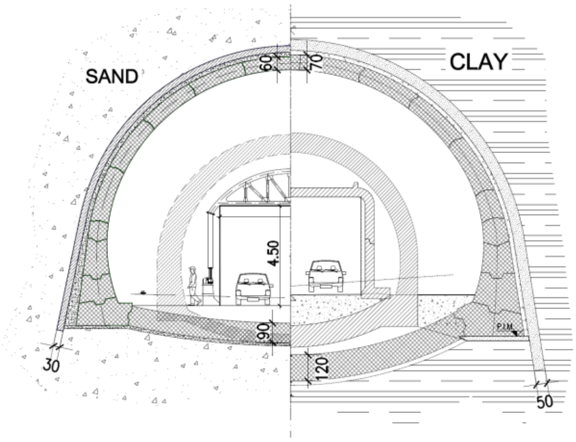

Figure 7. Comparison between the Nazzano tunnel section type (left) and that for Montedomini (right)

On the other hand, the maximum distance from the face and the length of the advance cycle remained unchanged with respect to the Nazzano Tunnel at 6.5 m and 4.0 m respectively.

Obviously, with account also taken for the structural aspects of the design just mentioned, the construction site layout with very reduced working spaces also penalises production greatly for the Montedomini Tunnel.

As can be seen in Figure 8 and Figure 9, the first change made to improve the situation was to the traffic protection shield. The movable steel shield solution with a curved extrados in the crown, already described, was abandoned and a fixed shield approximately 400 m in length was constructed entirely in reinforced concrete with a square profile to the extrados.

With this solution the protection shield can house a true and genuine construction site area on top of it, along which materials needed at the face can be transported (prefabricated concrete segments for the crown of the final linings, concrete to fill the precut and the concrete segments just mentioned, by using a system of tubes and pumps housed inside it).

This change resulted firstly in a safer working environment, by reducing the transit of vehicles to and from the face, with a substantial reduction in the risk of accidents for site personnel who can access the face by moving on the upper surface of the shield without interfering in any way with vehicles moving along the sides of the roadway and the tunnel to be widened.

This system has considerable advantages also in terms of:

- the management of gas risk, already very low;

Figure 8. Montedomini tunnel: traffic protection shield

Figure 9. Montedomini tunnel: construction site area above the shield

- health in terms of air cleanliness and noise in the working environment, as a result of its total separation from the motor traffic below;
- easier communication between the two sides of the tunnel being widened. Operations at the face are improved as a result of two sim-ple connecting ramps at the sides of the shield for the transport of materials, maintenance intervention and first-aid rescue operations if necessary without having to use an overhead crane

which is extremely onerous and difficult to manage in that context.

Furthermore, a shield that is longer than the tunnel makes it possible to also commence work to prepare the portals on the side opposite to that of tunnel advance and it also makes it possible to organise another production unit if the tunnel to be widened is longer than 500 m, in order to be able to advance on two faces.

In terms of the management of the traffic below, continuous protection along the whole tunnel reduces "distraction" risks for users, who find themselves travelling inside an environment with a constant cross-section, which does not change as opposed to that of the self-propelled steel shield used at Nazzano. On the other hand, greater vigilance is required to prevent vehicles higher than the shield from entering. They could get caught in it and cause considerable problems for traffic, since the shield cannot be moved at all.

On the basis of the results of the production analyses described previously, changes were made at the design stage to reduce the number of prefabricated lining arches to be erected for each 4 m advance cycle from four (1 m in length each) to three (1.33 m in length each). This reduces erection operations by 25% with clear benefits also in the consequent reduction in the number of ancillary operations (parking the M.M., etc.), because the time taken to install a segment depends little on its size, if the M.M. used for erection is properly designed.

In order to carry out this modification and gain further benefits in terms of the management of maintenance stages, an important change was also made to the equipment used to perform the precutting and active arch operations.

In fact widening the Montedomini Tunnel without halting traffic will not be performed by using a single M.M. consisting of two portals joined together as at Nazzano, but by two separate machines, one dedicated exclusively to mechanical precutting and one dedicated exclusively to erecting the active arch (Figure10).

The main components of the precutting machine are as follows (Figure 11):

1. Cutting unit
2. Front carriage support arch
3. Rear ancillary equipment support arch
4. Right and left base frames
5. Work platforms and driving cabin
6. Sprayer arm

Figure10. Montedomini Tunnel: the two machines used to widen the tunnel in the presence of traffic

Figure 11. Mechanical precutting machine

The front arch consists of three steel structural components (two side struts and one crown): it is possible during construction to raise one of the side struts on one side when the cutter is located on the other side, in order to make operations to remove spoil from the precut incision easier.

The main components of the segment erection machine are as follows (Figure 12):

1. Erector arm
2. Mobile platform
3. Front and rear arch
4. Brackets
5. Right and left base frames

The main advantage of separating the functions of the two machines is that it is possible to make more powerful and better performing equipment capable of making larger precut incisions than on the Nazzano Tunnel and of erecting heavier concrete segments. The two machines are structured so that the segment erection machine can travel above the precutting machine both when moving towards the face and when returning to its parked position at approximately 30-40 m from the face

Figure 12. Segment erection machine

Finally advantages also exist for maintenance management, because the downtime for the individual machines is longer than the downtime possible for a multifunction machine, which basically only occurs during the excavation stages.

The decision to separate the precutting and active arch machines also implicitly confirmed the validity of some decisions made at Nazzano concerning the need to carry out the excavation stage and the spoil removal stage using conventional excavators and diggers, rather than by using tools fitted on the portals of the two machines.

The excavation cycle for the Montedomini Tunnel, similar to that employed in the Nazzano Tunnel, results from the improvements just described. The operational stages of the cycle are as follows:

1. mechanical precutting (the face is 6.5 m from the last assembled ring of the lining);
2. erection of two arches of the prefabricated concrete segment lining, each 1.33 m in length;
3. excavation for 2 m advance;
4. erection of one arch of the prefabricated concrete segment lining, 1.33 m in length;
5. excavation for 2 m advance.

Additional innovations regarded precutting spoil removal, which was carried out using automatic suction devices. These convey the spoil to an appropriate truck by means of a neoprene tube which easily reaches the areas concerned.

6.3 *Construction work*

Work to widen the Montedomini Tunnel without halting traffic began in September 2013. Only a few advance cycles had been carried out at the time of writing this paper. As a consequence, significant assessments or data analyses which might confirm the validity of the improvements made on the basis of better production performance are not possible.

However, optimisation of the traffic protection shield has already shown clear benefits, above all in terms of safety for site personnel and a healthy working environment. It is very probable that use of the shield as a construction site area, with a consequent increase in the efficiency of working spaces, will also bring considerable benefits in terms of an increase in daily production rates.

The validity of the decision to construct two machines for the two main stages of the advance cycle (mechanical precutting and erection lining segments) is still subject to assessments of the actual benefits produced. However, management of a precut of such large dimensions (3 m^3 per linear metre of advance), in fairly consistent ground very definitely led to this decision, which allows the use of a very powerful and high performing machine.

7 CONCLUSION

The “Nazzano Method” for widening a road, motorway, rail or metro tunnel without halting traffic is evolving with the second use in the world of this construction system, currently in progress in Italy in the Montedomini Tunnel on the A14 motorway. While the first application solved some of the operational problems of working in the very small spaces available for the operating machinery, although not without difficulty, on the Montedomini Tunnel efforts have been made to make improvements to address the main difficulties of the method both at the design stage and also in terms of the organisation of the production cycle.

The traffic reduction shield has been transformed from an obstacle and constraint into an operational opportunity and now constitutes the main and safest route to supply the face.

The reduction in the concrete segment erection operations from 4 to 3 per advance cycle and other improvements to all operational stages, which are related also to technological progress that has been made over the last 10 years, should make it possible to achieve even more encouraging production objectives than those already reached in widening the Nazzano Tunnel without halting traffic.

To conclude it is with impatience that we wait today for the conclusion of the start-up and fine-tuning period of the works, in order to be able to write another page of progress in a very special technology for the expansion of underground infrastructures.

In any event, the experience acquired to date with the Nazzano Tunnel and the Montedomini Tunnel demonstrates that today widening a tunnel without halting traffic is a real possibility to be considered every time the upgrade of an existing infrastructure with sections that run underground in order to satisfy new and more difficult traffic conditions must be assessed. The Nazzano Method, with its subsequent innovations and improvements, may find its natural ground for development where no alternatives are possible as in the case of urban or road or rail tunnels with exits onto viaducts or other works of art.

Table 2. Comparison of the costs of widening an existing tunnel with the Nazzano Method and widening with a third tunnel per linear metre of tunnel excavation.

THE WORK PERFORMED	COST PER LINEAR METRE OF TUNNEL [€/m]
Widening an existing tunnel - total cost net of safety costs:	57,350.00
Widening with a third tunnel - total cost net of safety costs:	55,350.00

An examination of the data shows that on a like-for-like basis the costs for the two solutions are very similar, with a difference of 3.65% of the cost for widening the existing tunnel The extra safety costs for widening an existing tunnel (a traffic protection shield) can reach 8.90% of the cost of the works and therefore do not substantially alter the financial feasibility of the project itself. As a percentage these costs tend to reduce as the length of the tunnel to be widened and therefore the overall costs of the project increase.

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