

VISIONS IN PLANNING TUNNELS & UNDERGROUND SPACE

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Abstract

Many projects exercising great vision can now be constructed and operated because of recent significant advances in technology. Accordingly, planning of tunnels and underground space can now be bold and visionary because new technology will develop during and after the planning stages that will positively affect the feasibility of the project. In fact, it will be shown that technology is now developing at such a fast rate that planners and decision makers have both great opportunities and challenges to be sure that their planned tunnel or underground space will be at or exceeding the State of the Art as of the time the underground facility will be constructed. These and other planning issues are discussed.

1.0 INTRODUCTION

1.1 General

Big infrastructure projects such as transportation, water & wastewater systems and other major underground projects are generally planned 1 or 2 decades ahead. Moreover, the serviceable life of many tunnels is often over one century. These issues create a great challenge to planners and decision makers and illustrate the great importance of careful but creative vision during planning of these long-term projects. Planners must consider not only lessons learned from the past but also what new concepts and innovations may develop over an extremely long time.

1.2 Tunneller's Vision

There are two definitions for the phrase, "Tunnel Vision." In medicine, it is a visual problem which is the loss of peripheral vision. One sees clearly only in the center of one's vision but the vision around the periphery is dim and blurred. There is another definition for Tunnel Vision; that of "Narrow Mindedness" which means an extremely narrow point of view whereby people may they know the answer to a question before they study the question. This could be either consciously or sub-consciously. Fortunately, our tunnel planners do not experience this trait or tunnels such many of those visionary projects now under construction would not have been planned or built.

Instead, we should congratulate our tunnel planners for being creative and re-define what the author will call "Tunneller's Vision" which embodies many excellent traits needed to be visionary including: Imagination, Perception, Foresight, Awareness, and Common Sense while using Lessons Learned as a guide.

Our tunnelling industry has also overcome the reluctance to innovate. In the past, innovative thought has been curtailed because of legal traps and the unwise emotion felt by some of not wanting to be the first to use untried techniques, even though they are excellent solutions. Again, fortunately, our industry, including our planners and decision makers must be congratulated on creating and proposing innovations both in planning, construction and operation in order to get the job done. We should be proud of the innovations implemented by our industry routinely. More importantly, we should urge our planners and decision makers to be continue to be bold, creative, and visionary because our industry has "tunneller's vision" and the capability to meet every challenge

1.3 Challenges to Planners and Decision Makers

What are the challenges to Planners and Decision Makers? They are not only numerous but they also change in significance with time as the process of planning develops over time. These challenges include:

- Population & Demographics
 - How many people use the tunnel and where the tunnel is needed

- How these demographics change with time especially when a tunnel or underground facility is put into operation
- How the project itself may affect local demographics
- Social Trends
 - Changing Economic & Social Values
 - Changes in transportation modes with economic development
 - Change in transportation mode such as personal auto vs. transit values
 - Increased interest for water and wastewater improvements; sanitation and quality of life
 - Changing Environmental Values
 - This is likely to be one of the biggest factors in the demand for future tunnels
 - Increasing interest in preserving the environment
 - Acceptance that preserving the environment is a worthwhile goal even if it costs a little more
- Tunnel Technology likely to be available
 - Tools and Methods
 - Technical & Contractual
 - Innovative tunnel concepts
- Future Non-Tunnelling Technology Developments
 - Improvements in technology outside of our industry will dramatically affect the type of tunnels and their design criteria
 - Especially true in Transport
 - Dwindling oil supplies, higher oil prices may accelerate fuel cell, electric, and/or hybrid development whose use eventually may reduce emissions and ventilation requirements especially in long tunnels
 - Consider concepts such as Maglev, or other breakthrough propulsion systems
- Need for Systematic Consideration of Both Risks and Opportunities in Tunnel Planning
 - Most importantly, begin a formal systematic program as soon as a tunnel is considered to identify and characterize risks but also to identify opportunities that should be considered.

2.0 PLANNING NEEDS FOR WORLD POPULATION DEMANDS

It is well-known that the world's population is increasing at a staggering pace. In October, 1999, the world population passed the 6 Billion mark. A major factor in world demographics that is very important to tunnel planning, is that, in the future, most of the world's population will live, not in rural areas, but in urban cities. In 1950, only about 1/3 of the world's population lived in urban areas. By October, 1999, about 1/2 of the 6 Billion people lived in urban areas.

Because of this, cities are becoming extremely large with huge infrastructure requirements. So large, that the United Nations and other world bodies are giving special attention to those cities in which more than 10 Million people live, the so-called Megacities. In 2001, there were only 19 Megacities. By 2015 it is estimated that there will be about 60 Megacities and most of these cities will be in the Developing World. The trend will continue. By 2030, it is estimated that 4.9 Billion people will live in cities which is 60% of the estimated 8.1 Billion world population. Planners and decision makers must realize that an enormous amount of infrastructure must be constructed not just for these cities to be sustainable, but just for them just to survive. In fact, there may not be enough tunnellers to safely construct and operate such a large number of tunnels in such a short time.

Fortunately for the underground industry, if the environment and sustainable development are considered, the underground is often the construction method of choice for much of the infrastructure. It is essential that those of us in the industry be pro-active to inform the public, the media and city officials and planners, at very early stages of a city's growth, of the importance of the underground to sustainable development and to quality of life.

More use of underground space will be beneficial to sustainability of cities. More planning of general underground space such as living and office spaces will be important but also long tunnels will be needed to maintain the efficiency of the transportation networks between these Megacities.

3.0 PAST DEVELOPMENT OF TUNNELLING TECHNOLOGY

3.1 General Comments on Tunnelling Technology Development

Major mining and civil works schemes during ancient times and throughout the Middle Ages were, in their own right, great feats in their own time. Our most relevant civil engineering history, however, is in the last 1 ½ Centuries. Our forefathers in the tunnelling industry back then had great visions of technological goals that we have only been able to achieve in the last few decades. Their vision regularly exceeded practical limitations of technology during their life.

Though there were several advances, the development of tunnelling technology was very slow from 1850 to almost 1950. The Channel Tunnel took over a Century to realize the dream, not only for political reasons but also for technical reasons. Since technological changes were slow to develop, tunnel planners knew there was not much chance of significant innovations that might make a project feasible. Now (2006), just the opposite is true; innovations are becoming the norm and this rapid development in technology and innovations must be taken into account by planners. This opens a whole new set of visionary requirements for tunnel planners.

The author was fortunate to have been involved in pioneering work on innovative tunnel support systems in the late 1960's at the University of Illinois in Champaign-Urbana for a project for the U.S. Federal Railroad Administration (Parker, 1972). The impetus for this work was the ambitious concept of a tunnel or series of rail tunnels from Washington DC to Boston, a distance of some 750 km. The concept was bold and visionary but was never constructed for many reasons including cost. The project team found that very few ideas were truly new; almost everything had been tried before.

Our forefathers not only had great visions when they planned tunnels but, as will be seen later, they actually tried some of these great ideas. Subsequently, progress in technology made their ideas feasible; however, usually those ideas were put into practice decades or sometimes a century later (Parker, 1999).

3.2 Pre 1950 Tunnelling Technology Development

Prior to 1900, practicing tunnel planners, designers, and contractors had great vision and developed some extraordinary concepts for tunnel construction and operation. Unfortunately, more frequently than not, they were unsuccessful, mainly because technology had not progressed far enough to support their ideas and visions. Let's look at a few examples.

It is general knowledge that modern tunnel boring machines (TBMs) are a relatively recent development in our industry, say since the 1950's. However, the first mechanized tunnel machine was created and tried a century earlier! It was a percussion-type machine that was tried unsuccessfully on the 12 km long Mt. Cenis Tunnel (also known as the Frejus Tunnel) from Italy to France (Stack, 1982). Interesting to the theme of this conference on Long Tunnels is the fact that this innovation (as well as the first use of the compressed air drill) took place in this tunnel which was the first of the long alpine tunnels. The second mechanized tunnel machine, also unsuccessful, was built for the 8-km-long Hoosac Tunnel in Massachusetts, USA in 1853. There were numerous attempts over the next century to build and use a form of mechanized tunnelling machine. A few were fairly successful, including machines which successfully bored a couple of km for an earlier attempt at constructing the Channel Tunnel. But, whatever the reason, technology was insufficient to permit technically and cost effective machine excavation and there was a time-span of over a century before TBMs began to become practical.

Pressurized-face machines also took a long time to develop to a practical method of excavation. In 1874, Greathead patented a tunnelling concept that consisted of a shield with water under pressure at the face, excavation using water jets, and muck being pumped out as a slurry. There was even a chamber for breaking up cobbles and boulders. For almost a century there were a few attempts to develop machines with pressure on the face but technology was again insufficient to permit technically and cost-effective machine excavation.

Gunite, the forerunner to shotcrete was first developed in the USA around the turn of the century when Carl Akeley invented the Cement Gun to apply mortar over skeletal frameworks of prehistoric animals for Chicago's Field Museum. Although tried in an experimental mine in Pittsburgh in 1914, it wasn't until 1952 on the Swiss Maggia Hydroelectric project before tunnels were solely supported by shotcrete (Parker, 2001). Again, there was a ½ century span between vision and practical application.

3.3 Development of Technology: 1950 to Present

After about 1950, technology started to catch up with our vision and many of our forefather's ideas became reality. James S. Robins built an 8-m-diameter rotary TBM which successfully excavated Pierre Shale at Oahe Dam in the USA and then pioneered the use of solely using disc cutters on a TBM cutterhead on a small diameter tunnel in Toronto. Although there was a long, difficult period for hard-rock TBMs, ultimately technology permitted TBMs to overcome hard rock to where they are now routinely used to excavate most tunnels, even long tunnels. Technology is still developing for these TBMs at a rapid pace in attempts to make TBMs capable of controlling the more difficult ground conditions.

After more than a Century delay since Greathead's patent, pressurized-face TBMs were also the benefactor of the rapid development of technology in the latter half of the 20th Century. In the 1960s, several developments took place all over the world that made these machines more feasible technically. These took place in Japan, Germany, England, Mexico, USA, Canada and elsewhere. Earth Pressure Balance and Slurry machines now are commonplace on routine projects. Now, there are various concepts for handling mixed-face conditions to make machines more feasible for rock tunnels that will also pass through fault zones with differing ground conditions. Such machines are now designed to be able to be converted with some, but acceptable, effort from hard rock mode to a pressurized-face mode, becoming increasingly adaptable and are even being used on longer tunnels.

Steel fiber reinforced shotcrete (SFRS) was developed in the USA around 1970. The author worked on the practical development of SFRS at the University of Illinois in the early 1970's and published his results in his Ph.D. thesis in 1976 (Parker, 2001). Despite its great promise, it took another decade before SFRS became common in tunnel construction but SFRS is now routinely used.

These examples illustrate that technology has started to catch up with the vision of the planners and designers. The message to the planners and designers is that our industry is very creative and can overcome any challenge. Thus, planners should be bold and daring in the planning of projects.

4.0 AVAILABLE TOOLS FOR PLANNERS

4.1 Previous Planners Lacked the Tools

In the 1950s and 1960s, planners did not have many of the advances that we now enjoy (2006). Think what planners could have done if they knew that these tools would exist when their tunnel was finally constructed. These are too numerous to cover adequately in this paper but they include the following:

- TBMs of any kind
- Earth Pressure Balance Machine (EPB)
- Slurry Face Tunnelling Machine (SFM)
- Shotcrete
- Sequential Excavation Method (SEM/NATM)
- Microtunnels
- Single Pass Lining of Concrete Segments
- Waterproof Membrane
- Advanced Geotechnical Investigation Techniques
- Numerous Ground Improvement Techniques
 - Jet Grouting
 - Soil Mixing
 - Compaction/Compensation Grouting
 - Efficient and effective grouting in front of TBM

Even rock bolts were just being accepted by civil engineering projects in the 1950s although they had been used successfully in the mining industry.

Each of these (and the many others not listed) make tunnels and underground construction today more technically and financially feasible. Had planners been bold and daring back in the 1950's, many more tunnel projects would have been proposed and built in increasingly more difficult conditions. Again, this is proof of the strength and creativity of our tunnelling industry. If a planner can dream it up, our industry can get it done.

4.2 Past and Current Successes for Current Planner's Consideration

Some of the past and current successful techniques that planners can use to assure themselves that they can be bold in their planning include the following:

- Tunnel Construction & Operation Techniques
 - Large & Adaptable TBMs (Getting Larger and More Adaptable)
 - SEM/NATM (New Techniques & Methods of Support & Monitoring)
 - Microtunnels & HDD
 - Jet Fan Ventilation
- Innovative Tunnel & Underground Concepts (Use and Configuration)
 - A86 Paris (6 vs 2 lanes)
 - SMART Kuala Lumpur (Highway and Flood Control)
 - CSO Wastewater Storage Tunnels
 - Submerged Floating Tunnels (SFT)
 - Long & Deep Tunnels
 - Underground Space Use
- Concepts from other Industries
 - MagLev (Or other Propulsion Systems)
 - Fuel Cells, Electric, or Hybrid Vehicles
- Contractual, Financial, and Managerial Concepts
 - Structured Risk Management Principles
 - Identification of Opportunities
 - Life-Cycle Cost Concepts
 - Advanced Cost Estimating concepts
 - Alternative Financing

These are just a few of a large number of techniques and tools that Planners and Decision Makers now have to make them more comfortable as they look with vision more boldly into the future to propose and to successfully implement more tunnel and underground projects.

4.3 Techniques for Risk Management & Identification of Opportunities

Very important among these is the recommendation that tunnel owners and planners begin to use systematic risk management principles to identify any risks in a way that directs the rest of the planning and construction process to minimize those risks. This systematic procedure must be done as early as possible in the stages of a project (pre-conceptual or idea stage). The development of Risk Registers is often done in meetings of experienced experts who identify the risks and solutions. This systematic risk management work then is carried on and updated all the way through design and construction. The risks to be considered should be broad and also include risks of cost, schedule, environment, public acceptance, adjacent owners & third-party intervention, politics, etc. in addition to the technical risks that always immediately come to mind. The International Tunnelling Association (ITA) has published guidelines for risk management in tunnelling (ITA, 2004).

Fortunately, the same concepts and tools can be used to identify value engineering ideas, as well as to identify broad ideas and opportunities (including “thinking out of the box”).

4.4 Life-Cycle Cost Principles

Tunnels often remain in service for over a century. Accordingly, decisions about whether a certain infrastructure should be a tunnel, or not, should be made on considerations of Life-Cycle Cost, not Initial Capital Cost. This is a difficult concept to implement but it is important for planners and decision makers to avoid the pitfall of decisions based on initial capital cost. Finally, using principles similar to those used in Risk Management, the likely cost of a tunnel or underground facility and also its planning and construction schedule should be developed and reported as a range, not as a single number. This has been done very successfully on several projects such as the Alaskan Way Viaduct Replacement Project in Seattle, Washington, USS (Reilly, 2004)

Obviously, the life-cycle costs should include future operational and maintenance costs. However, the cost analyses should also include realistic allowances for equivalent financial benefits from environmental and social improvements associated with tunnels.

4.5 Construction Technology

There are many tunnel construction and operation techniques that planners should consider for all projects, including general underground space facilities. These include the large and adaptable TBMs that have evolved over the years to cope with mixed-face conditions. Naturally, Sequential Excavation Methods (SEM/NATM) are always available when even the TBMs are not appropriate, including those openings with irregular geometry. Microtunnels and Horizontal Directional Drilling methods (HDD) are now being considered as methods to supplement the construction of larger tunnels, to include pipe-roof techniques etc (Sterling, 2004).

There are new concepts being developed all the time for safe ventilation of tunnels (including underground space facilities and long tunnels) during construction. The development of jet fans now makes it possible to build longer road tunnels (within limits) without having to build and maintain a large fixed ventilation fans for permanent works.

5.0 VISIONARY BOLD AND DARING TUNNEL CONCEPTS

5.1 Current Visionary Concepts Being Implemented

There are many innovative tunnel concepts that have evolved because the project planners were highly creative and “thought out of the box.” These include the A86 road tunnel project in Paris. By changing the rules and requiring all vehicles that use one of their tunnels be less than 2-m-high, the owner/concessionaire is able to fit 4 lanes of traffic plus 2 breakdown lanes (in a double-deck configuration) in a 11.6 m-outside-diameter tunnel. There is even a possibility for future expansion to have 3 lanes on each deck for a total of 6 lanes in a tunnel that, at least in the USA and elsewhere in the world, can only fit 2 lanes of traffic. That makes the cost of those tunnels per km per lane on the order of $\frac{1}{2}$ to $\frac{1}{3}$ of the cost for traditional configurations. Moreover, such a tunnel can be constructed using more readily available standard size TBM’s in a shorter construction time and with less disruption to the public.

Another innovative concept is the SMART tunnel project in Kuala Lumpur. This double-deck tunnel is specially configured to handle both auto traffic and floodwater. During low and medium flows, water flows beneath the lower deck while cars are still travelling through the tunnel. However, when a very big flood occurs, cars are removed and the flood waters are passed through the entire tunnel including the roadway. This way, the public gets two end uses for the tunnel for a price and construction disruption that is less than that of two separate tunnels. Moreover, the cost of the tunnel is shared by two groups making each easier to afford. The concept of using tunnels to store wastewater during a storm, such as the Chicago TARP project and other CSO storage projects, is another dual use of tunnels.

In Seattle, a 50-year-old viaduct which follows the waterfront was damaged by an earthquake and needs replacing. Also, the seawall just beneath the viaduct also needs replacing. Planners and decision makers are considering a double-deck cut and cover roadway whose outboard wall will be designed to be the new seawall. This new structure will replace both the viaduct and the seawall with one structure with an overall savings in cost, schedule, and reduced disruption to the public. Moreover, the cost would be shared by both road and waterfront authorities.

5.2 Future Visionary Thinking

The Swiss Metro is a bold concept developed for a very high speed transportation network in Switzerland which has been extended conceptually to other parts of Europe. Maglev trains would be propelled at very high speed through tunnels in a partial vacuum. A comparable scheme for North America, the AmericanMetro has been proposed by Swartzwelter (2003). A network of tunnels between major cities would be constructed for very high speed (1000 km/hour) transfer of people and goods.

All of the proposed long ocean tunnels in the planning stage now (2006) fall into the category of visionary and bold tunnels as was the Channel Tunnel for over a century. Like the Channel Tunnel, the author believes that technology will be developed to make the tunnels currently in the planning stage feasible as well.

Finally, a Submerged Floating Tunnel (SFT) has been proposed several times in various parts of the world but never built. Conceptually, the SFT can be a lot shorter tunnel which gives much greater flexibility in locating tunnel alignments & portals. SFT’s are a perfect example of “thinking out of the box.” It is so creative that one

can allow your imagination to soar on these types of projects. Recently, SFT's have been identified by the Discovery Channel as one idea for a crossing of very large body of water or maybe even an ocean. Such a concept has many non-technical obstacles which may prevent such a project to get farther than the conceptual stage. However, SFT engineers have identified the major issues to address to make such a concept work from a technical standpoint.

The author admits that some of these concepts may seem outrageous at the present time. However, the first three projects listed above either are in planning and construction or are already built.

5.3 Impact of Issues and Events Outside of the Tunnelling Industry

There are many issues and events outside of our industry that will have a significant impact on our planning for tunnels. Some of these issues we do not even know about yet but one of these is the price and availability of oil. There have been numerous claims over the past decades that the world would run out of oil, or otherwise cost too much, and that other fuels will be necessary. This has not happened yet but may happen, if nothing else, because of greatly increased demand for oil by developing countries. So there is a greater chance that the world will need other fuels, possibly to include hydrogen fuel cells or a hybrid.

Interestingly, the fuel cell is another concept that was invented in 1839 but did not gain any real practical use until used by NASA for space travel. The concept is being worked on by many countries and, in the USA; there are several local and regional agencies which have fuel cell or hybrid technology as a test. When hydrogen is the fuel, the only emission is water.

Hybrids are fast gaining popularity both in additional research and in practical applications by forward thinking and visionary travellers. Some use different fuels which may impact tunnel ventilation systems in various ways. Some, however charge large electric batteries which, when used to propel vehicles through tunnels would drastically reduce ventilation demands especially in long tunnels.

It may be preposterous to think that the internal combustion engine may be replaced or metamorphosed into something better, but stranger things have happened even within the author's lifetime such as the development of jet engines, space travel, television, computers, and air conditioning, cell phones, etc. The author is not predicting such a transformation in transportation may take place but one should think of what effect it would have on the design of the ventilation system and the operation of the tunnels if it were to take place. More likely, in the foreseeable future, some hybrids will become popular and the gasses our tunnel ventilation systems must deal with may decrease or may not increase as fast as predicted.

Another concept that may affect future tunnel planning is related to propulsion technology such as MagLev or other future propulsion breakthrough we don't even know about yet. There are Maglev systems in operation now but not in tunnels although the author understands that a maglev test track in Japan goes through a short section of tunnel. There is a lot of development, and reduction in cost, necessary to make Maglev, or any other new propulsion system worth considering for tunnels. However, there are some promising aspects if the concept becomes viable. For instance, the system is capable of being faster and it is environmentally friendly. Moreover, it can negotiate tighter curves and steeper grades both of which may allow tunnels to be shorter and therefore less costly. Whether such a concept will be technically feasible or cost effective is yet to be seen, but consideration of such a concept for bold and daring planning of future tunnels may not be unreasonable

5.4 Long Tunnels

Long tunnels have innovative concepts in themselves and they fall in the category of bold and daring. The long tunnels our forefather's built in the late 1800's and early 1900 were truly visionary and certainly bold and daring. These projects which were built a century ago prove the author's point that our industry will meet the needs of our visionary planners. Examples include the development of such methods and materials such as dynamite, compressed air drills, tunnel lighting, drill steel technology, new support systems etc. Long tunnels, especially long transportation tunnels, will be needed more and more as the Megacities develop around the world to connect the inner city with the outer suburbs and to interconnect the Megacities. They afford great reductions in travel time but also important reductions in fuel consumption and emissions. They also avoid the visual blight and they provide great environmental and sustainable development advantages over that of surface transportation that goes up and over the topography. In order to make these long tunnels more financially feasible and to make them more acceptable to the public, planners should definitely convert the strong environmental advantages to an equivalent cost savings to society.

Thus, the initial cost should be mitigated and offset by significant savings attributed to the environment over the years of operation. It is imperative for planners to consider the financial aspects of tunnels from a Life-Cycle Cost standpoint that also takes into account the accumulative equivalent financial benefits from saving the environment. Planners and decision makers must be courageous and convincing as they present a clear message of the overall advantages of tunnels to the media, public, politicians, and fellow decision makers.

5.5 Underground Space

There is no limit for the vision applied to the use of the underground space. Originally, man lived in caves carved by nature and later modified these natural shelters to suit changing needs. Now, thousands of years later, there are very interesting proposals for the use of underground space, especially from Japan. These include multi-modal complexes with offices, living quarters, public meeting areas, recreation, schools, etc all connected to the rest of the city at multi-modal stations. In addition, there are abundant locations where products (such as wine) are stored in bulk storage. There are wine cellars created for the wine owner's customers. In Kansas City in the United States, there are existing mined openings with over 450,000 square meters of space that is leased to various users for storage, office space, etc. Such major facilities require creative vision but can be planned boldly just like any other underground project.

6.0 CONCLUSIONS

In past years, planners did not have the luxury of the many tools and techniques that exist today. We should be very proud of our forefathers who had great vision and whose ideas were not achieved in their lifetime. Technology development was so slow from about 1850 to 1950 that their ideas did not materialize until technology made their schemes feasible.

Now, technology is keeping up with our ideas and vision which can be implemented relatively quickly. Accordingly, planners should be aggressive and bold in their plans for tunnels.

Owners and planners should use risk management principles from the very first time a tunnel solution is considered and carry out systematic risk management evaluations throughout planning, design and construction. These same principles should be used to systematically develop and implement value engineering and new opportunities, especially those thinking out of the box. This is particularly true for long tunnels that have abundant uncertainties.

It should always be remembered that tunnels, particularly long tunnels, are an investment, not a cost. Owners should develop ways to account for a financial credit resulting from environmental advantages especially for long transportation tunnels that accrue enormous environmental benefits to society. These environmental cost advantages should be incorporated into cost ranges that take into account the long service life of the tunnels by making the decision on Life Cycle Cost concepts, not initial capital cost.

The tunnel and underground industry is very creative and their ability to innovate has been proven many times. Owners and planners should have faith in the tunnel and underground industry. The industry will be up to any challenge so planners can plan boldly and with Tunneller's Vision.

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