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CENTER FOR TRANSPORTATION STUDIES

RESEARCH REPORT

DESIGN ISSUES RELATED TO ROAD TUNNELS

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This report is the first phase of a multi-year, ongoing research effort to identify and evaluate the impact of roadway design elements on driver behavior. The focus of this work is on road tunnels, but similar questions apply in other roadway environments.

The organization of this document reflects the research process employed in this project. First, the background is established indicating the increasing use of road tunnels to solve many planning problems. The next section identifies two groups of potential problems related to road tunnel design from the driver's point of view–those related to the general image of the tunnel, and those related to traffic flow and safety. Then, a case study of the proposed Stockholm tunnel system illustrates some real design responses to tunnel design problems. Based on these strategies and actual design approaches, a list of research questions is compiled. Finally, the two-phase research approach for this project is described. In phase one, computer models are developed and observations are made based on drive through simulations. In the second phase, subjects will be tested using the driving simulations at the Human Factors Research Lab to determine how their driving behavior is influenced by design elements.

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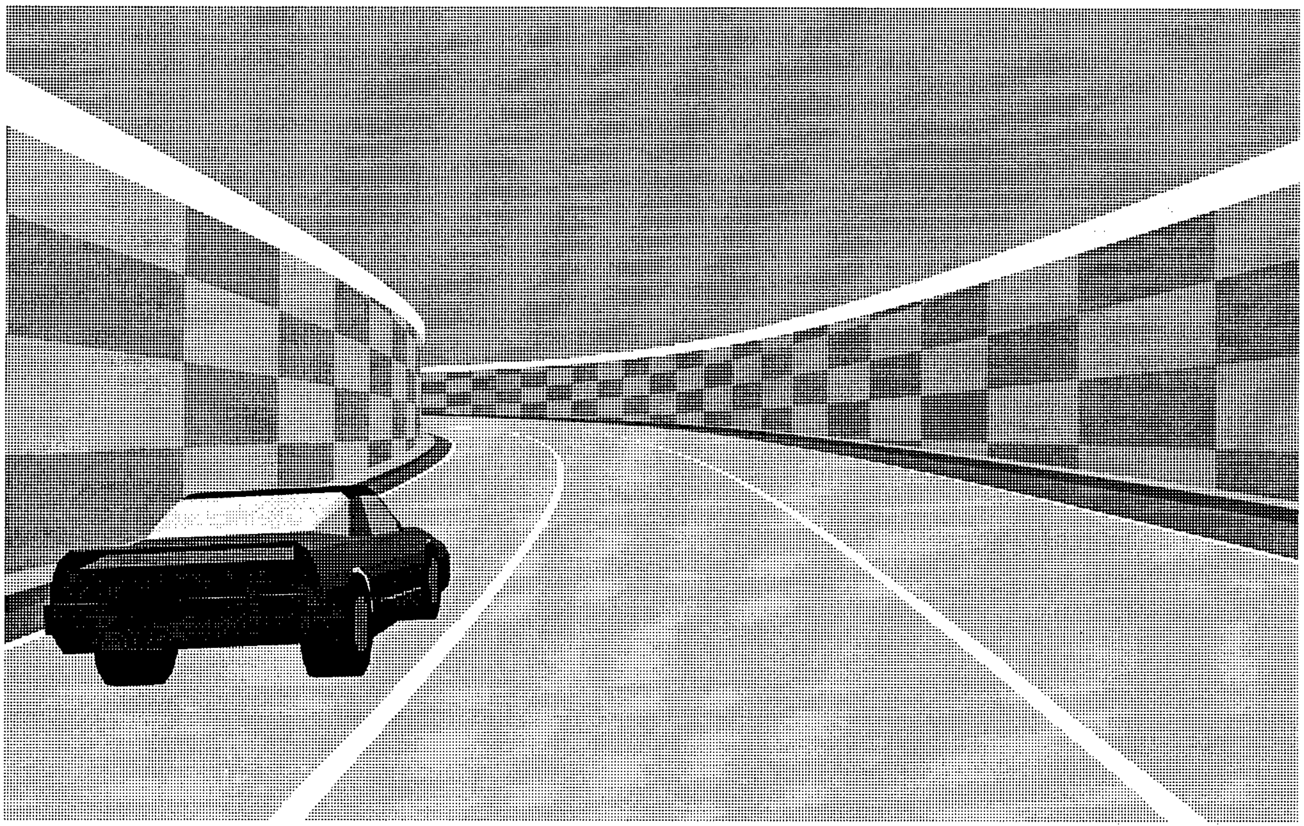

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References

1. Overview

This report is the first phase of a multi-year, ongoing research effort to identify and evaluate the impact of roadway design elements on driver behavior. The focus of this work is on road tunnels, but similar questions apply in other roadway environments.

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2. Background on Urban Underground Development

The current state of the urban environment is well known throughout the world. In many countries, migration toward urban areas puts great pressure on existing cities. Amenities, public open spaces, and infrastructure within cities are overused, while agricultural land surrounding urban areas is continually developed for other uses. Infrastructure presents the dual problem of being inadequate to handle new demands while requiring major upgrading due to its aging condition.

In most major cities, problems of traffic congestion, air pollution, and noise have degraded the environment. Overdevelopment and increased use of automobiles have gradually destroyed much of the human scale and character of older cities.

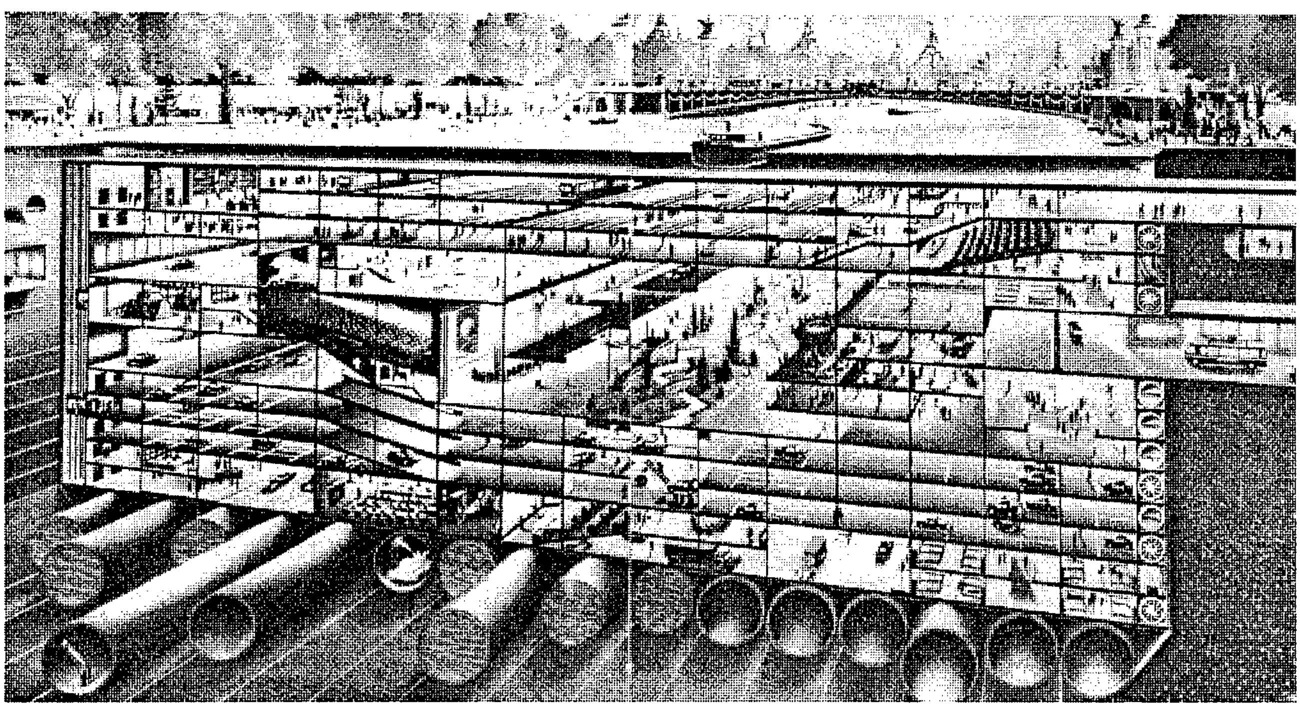

Figure 2-1: Concept for development beneath the Seine River in Paris.

Many central cities have become stressful and undesirable places. Against this background of specific urban problems are the general societal concerns over energy conservation and the environment. Clearly, a greater value is now being placed on the preservation of the cultural and historic centers of older cities. In addition, establishing greener, more pedestrian-friendly urban environments is also a trend. Most importantly, there is a clear recognition of the need to improve air and water quality, as well as to reduce the reliance on burning fossil fuels.

Dealing with this vast array of problems in urban settings is not a simple task. There are often limited choices to resolve many planning and development issues. The use of underground space is sometimes overlooked resource in city planning. It is certainly not a solution to every problem but offers another tool to be utilized. By placing certain functions underground, the surface can be used more effectively, and the overall urban environment improved.

While there are many underground facilities throughout the world, the remarkable future visions of some planners and designers reflect the increasing awareness and potential of the underground. These broader visions of underground development are of two types—extensive multiple use underground complexes as well as infrastructure systems such as long underground roadways in cities such as Stockholm and Paris.

Underground networks of space have been visualized as a comprehensive solution to congestion and environmental problems in many urban areas. In Paris, a multilevel underground city containing many functions and systems beneath the Seine River was envisioned in the 1960s. This concept was used to promote the eventual Les Halles development.

Recently, the high level of interest in underground space in Japan has resulted in similar visionary concepts. One project suggests major tunnels beneath Tokyo that would serve multiple functions. In addition to the typical transit and utility uses, underground corridors could serve as places for a communication network that is protected during disasters. Also, both waste and energy could be transported from substations in the city to central generation and disposal sites. This approach not only relieves congestion but can provide more efficient generation of energy and recycling of waste materials. In another Japanese proposal, large cylindrical structures extend 200 meters below grade to house completely subsurface living and working environments. Most of these concepts permit a major upgrading of the infrastructure that will eventually enable the surface to be rebuilt with more open space and a more efficient, attractive overall environment.

While many of these visionary concepts may never be actually constructed, extensive underground roadways are being designed or are under construction in dense, congested urban areas. In the United States, the Boston Central Artery project places a major freeway beneath the downtown area to improve traffic flow while enhancing the surface environment. By creating major road tunnels beneath Boston, elevated highways in the central city can be removed to create open space as well as more developable land.

Even more extensive underground ring road projects have been proposed in Paris, France and Stockholm, Sweden. Preliminary designs for the Stockholm project include a series of tunnels up to

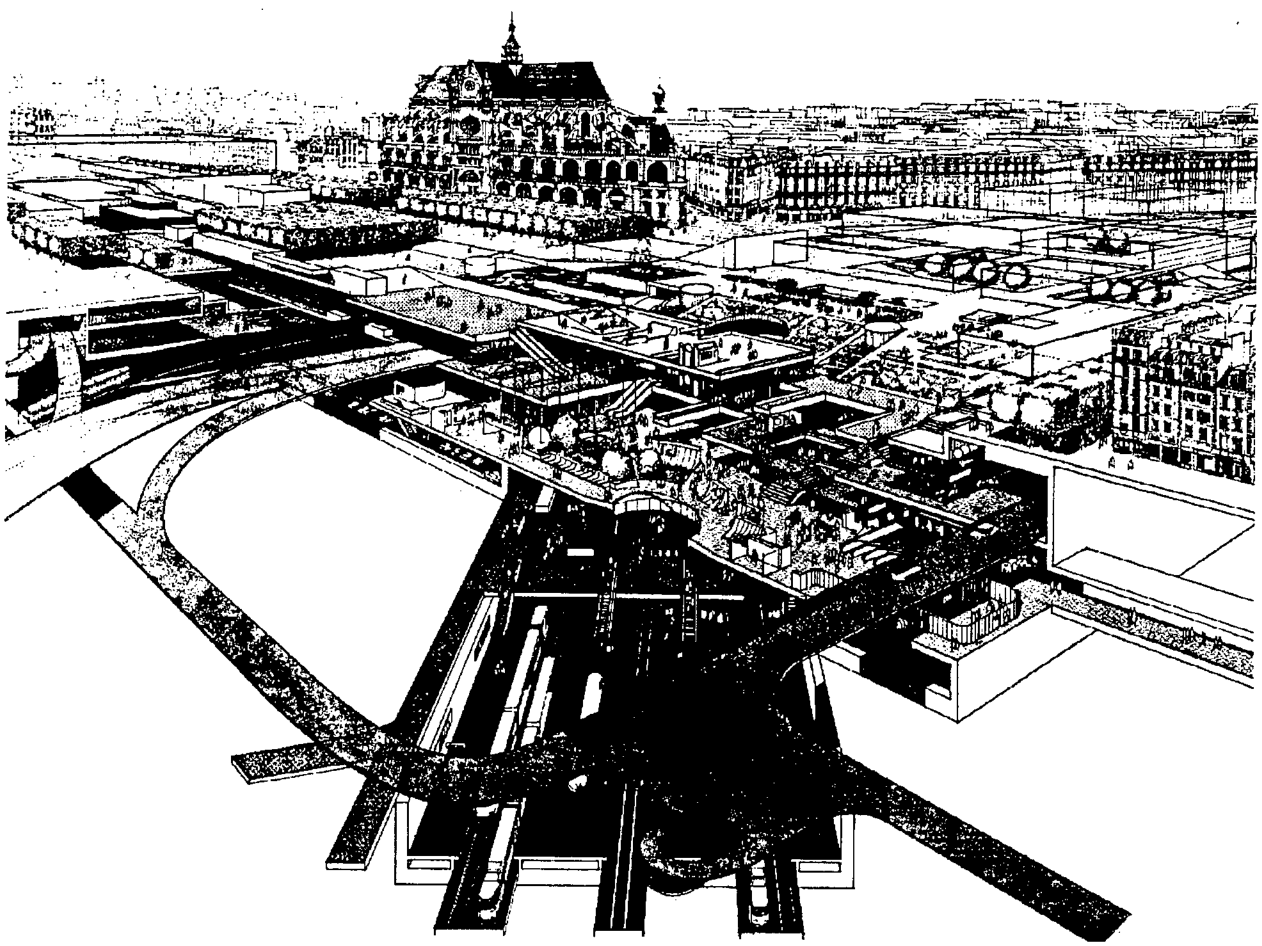

Figure 2-2: This drawing of the Les Halles development in Paris illustrates the complex geometry often found in urban underground facilities. This complexity and the inability of people to visualize the overall form and layout contribute to problems with spatial orientation.

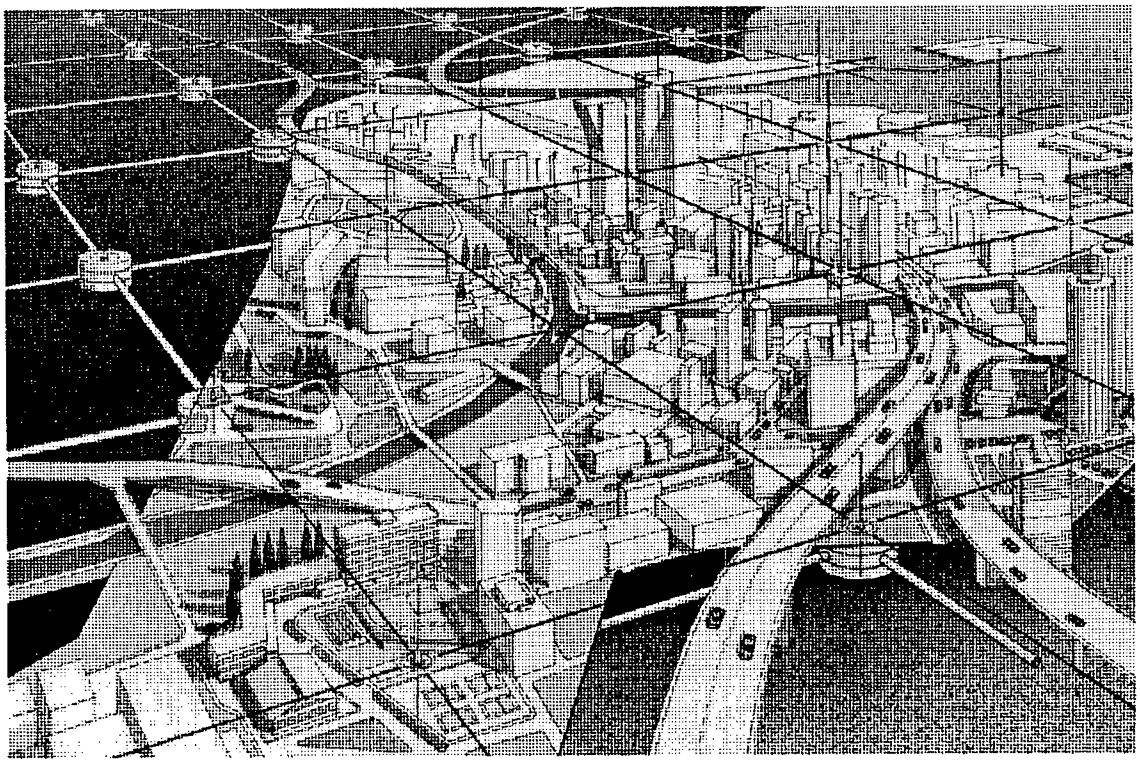

Figure 2-3: Geo-Grid concept for Tokyo developed by Shimizu Corporation. This illustrates an extensive network of underground space beneath Tokyo that can provide improved infrastructure and more open space on the surface in a congested urban environment.

12 kilometers long around the central city. The high levels of traffic that now must pass through the center of Stockholm can be diverted into the tunnel system. This creates the opportunity to restore the historic central city to a greener, more pedestrian-friendly environment while improving traffic flow in the region.

If roadways are placed underground, congestion and pollution can be reduced while the urban pedestrian environment can be enhanced. The visual clutter and noise from surface and elevated roadways can be eliminated. While pollution from vehicles still must be exhausted from road tunnels, it can be displaced from the central city and cleaned if necessary.

3. Problems in Enclosed Roadway Design

Placing automobiles underground in road tunnels is an appealing and effective solution to a number of urban problems—congestion, pollution, noise, poor use of surface land, and destruction of a safe, pedestrian environment. In designing underground roadways, however, there are several points of view to be considered. These include city planners, traffic and construction engineers, maintenance and operation personnel, as well as drivers (both those familiar and unfamiliar with the city). Often road tunnels are designed recognizing most of these points of view, but sometimes the driver's point of view is overlooked.

The experience of driving through a tunnel presents problems related to the ability to see the roadway, other vehicles, and the tunnel enclosure while moving at relatively high speeds. The sense of confinement, darkness, and limited range of view result in much less visual information than in the typical above grade roadway. Moreover, the experience of driving through poorly designed tunnels can contribute to a negative image of the urban environment.

PROBLEMS ASSOCIATED WITH UNDERGROUND FACILITIES IN GENERAL

Before examining road tunnels in particular, it is useful to review problems for people in underground facilities in general. The potential psychological problems associated with underground space include a sense of confinement or claustrophobia, fear of entrapment underground, and negative cultural and status associations, as well as associations with darkness, coldness, and dampness. Because underground buildings are often not visible from the exterior, they lack a distinct image and it may be difficult to find the entrance. Inside an underground space, there can be a lack of spatial orientation, and a lack of stimulation and connection to nature found in above-grade buildings with windows. The most notable physiological problems are lack of natural light, poor ventilation and air quality, and high humidity levels. A number of design strategies have been identified that can alleviate many of these concerns. These techniques can be applied to entrance design, layout and spatial configuration, interior design, lighting, and life safety (Carmody and Sterling 1993).

PROBLEMS ASSOCIATED WITH DRIVING IN TUNNELS

While the preceding lists of problems for people in underground buildings apply to virtually all types of facilities to some extent, the extremely long road tunnel projects recently proposed in some congested urban areas present some special concerns.

The problems discussed in this section are in two categories: (1) general psychological and image problems associated particularly with long tunnel systems, and (2) the specific traffic flow and safety problems inherent in the physical design of a tunnel enclosure. There is some research on these issues but it is limited to a few sources (Amundsen, 1992; Serrano and Blennemann, 1992). Many of the potential problems listed below have emerged as concerns during the design of recent road tunnel systems.

General Image Problems

The extremely long road tunnel projects recently proposed in some congested urban areas present some special concerns for people. These include:

1. Sense of confinement or claustrophobia
2. Fear of entrapment
3. Reduced visibility due to darkness
4. Monotonous visual environment
5. Lack of orientation
6. Lack of connection to the surface
7. Negative city image or lack of image

The first four problems cited here are often mentioned in relation to long dark mountain or undersea tunnels. A small percentage of people will avoid these tunnels entirely while a larger group will use them but feel uncomfortable doing so. An example of traditional mountain tunnel design is the 11-kilometer-long Mont Blanc tunnel connecting France and Italy (Figure 3-1). It is dark, oppressive, confining, and monotonous evoking many of the most negative associations with tunnels.

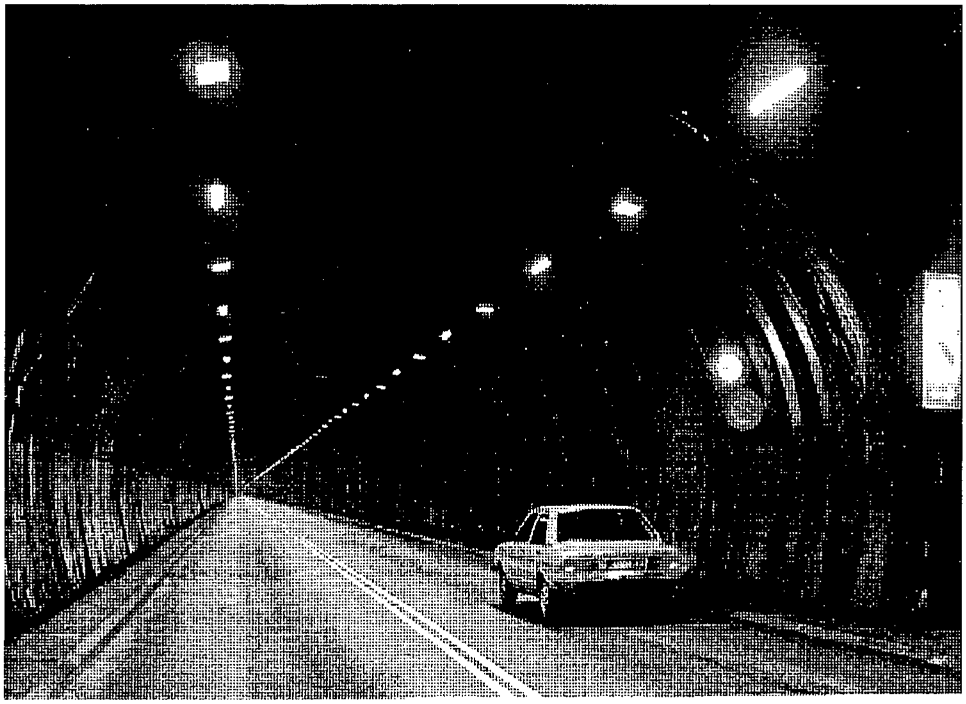

Figure 3-1: The 11-kilometer long Mont Blanc tunnel connecting France and Italy evokes many negative associations with tunnels. It is dark, oppressive, confining, and monotonous.

Mountain and undersea tunnels are often the only route available and thus are utilized regardless of people's feelings about them. Urban road tunnel systems, such as the one proposed in Stockholm, Sweden, are not always the only route choice and therefore may require a higher standard of acceptability. In addition, the experience of driving through the city is lost, affecting both the drivers orientation as well as their image of the city.

Traffic Flow and Safety Problems

Entering and driving through a tunnel can affect visibility and thus influence speed and the ability to respond quickly to incidents in the roadway. These traffic flow and safety concerns apply to both long, complex tunnels as well as simpler, shorter tunnels. Specifically, researchers have noted the following problems:

1. Drivers slow down at tunnel entrances. This appears to be related both to the change in light levels as well as the experience of going from an open road into a confined space. The portal design seems to affect this perception of an abrupt transition.

2. Drivers increase speed when the roadway slopes downward and reduce speed as it slopes upward. Unlike drivers on open roadways with numerous visual cues, tunnel drivers do not always have reference points to determine their sense of speed or relative grade. When visual elements like construction joints are perpendicular or parallel to the roadway instead of being truly horizontal or vertical, the sense of grade change seems to be diminished. Consequently, increases and decreases in speed impede traffic flow and lead to greater accident risk.
3. Compared to an above-grade roadway, visibility at curves is generally more limited in tunnels. This limited view of what lies ahead combined with a lack of visual cues makes it difficult to read the curvature of the tunnel walls and roadway to properly adjust speed. This can contribute to reducing speed and impeding traffic flow, or to an inability to stop quickly if required.
4. If the tunnel walls are too close to the roadway, drivers will stay a certain distance away. This may be unsafe if it causes drivers to be partly in another lane of traffic.

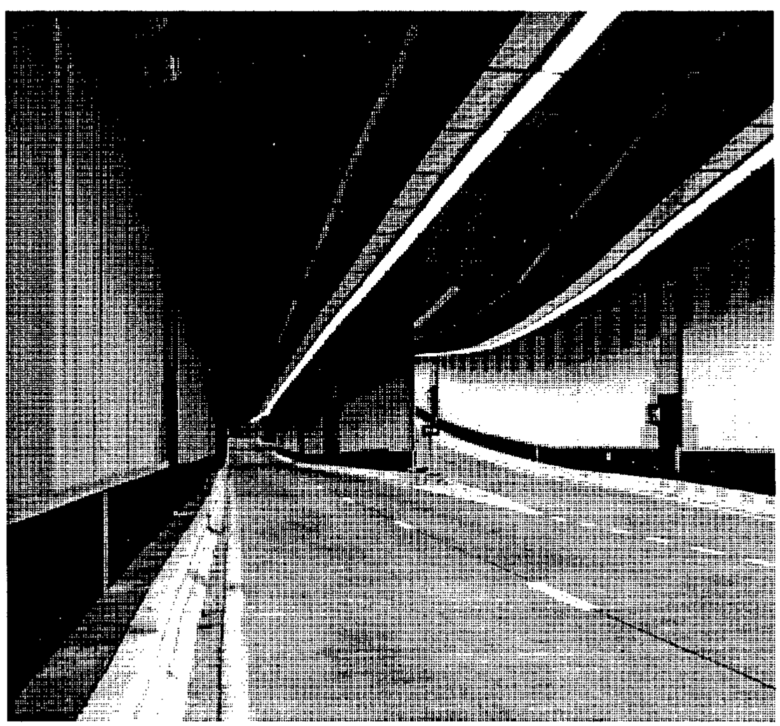

Figure 3-2: This Belgian tunnel is well lighted and uses color to enhance the interior design. However, it still illustrates the problem of limited visibility at entrances and exits within road tunnels.

4. Design Strategies

Before examining the specific strategies related to tunnel design, it is useful to explore some overall goals of highway design from the driver's point of view. Of course, the primary goals of highway design are to provide a safe, efficient means of driving from one place to another. Beyond this, however, are some additional goals that relate to the quality of the experience of a driver. In the book, *View from the Road*, Donald Appleyard and Kevin Lynch explored this problem.

> *"... roadwatching is a delight, and the highway is—or at least might be—a work of art. The view from the road can be a dramatic play of space and motion, of light and texture, all on a new scale. These long sequences could make our vast metropolitan areas comprehensible: the driver would see how the city is organized, what it symbolizes, how people use it, how it relates to him. To our way of thinking, the highway is the great neglected opportunity in city design" (Appleyard and Lynch 1964).*

Appleyard and Lynch suggested some basic goals in road design:

- Create a rich, coherent sequential form. This is built from a sensation of space and motion using modulation of light, color, texture, or detail.
- Clarify and strengthen the driver's image of the environment. The design should help the driver locate himself and features of the landscape. The driver should develop a distinct, well-structured image using key elements that form a city such as landmarks, paths, nodes, edges, and districts.
- Deepen the observer's grasp of the meaning of the environment. The design should give an understanding of the use, history, nature, and symbolism of the highway and its surrounding landscape.

It is interesting to note that in the examples given by Lynch and Appleyard, a short tunnel is an exciting event along a road sequence; however, an extremely long tunnel lacks most of the qualities desired in a highway driving experience.

The specific design strategies to meet these goals and alleviate the problems discussed earlier are discussed in two categories: (1) strategies related to the overall system image (associated particularly with long tunnel systems), and (2) strategies related to traffic flow and safety problems inherent in the physical design of a tunnel enclosure.

Design Strategies to Improve General Image Problems

For long, complex urban systems, it is important to create a distinct system image with entrances and exits in simple, understandable patterns. To enhance orientation, entrances and exits should be associated with well-known streets and districts. Clear information should be provided regarding location of exits and entrances and to explain emergency systems. If possible, provide visual connections to the surface both for orientation and to provide visual relief from the tunnel. Within the tunnel create a sense of spaciousness and lightness as well as variety and stimulation.

Listed below are possible tunnel design strategies that can be used to meet the design objectives stated above. These strategies should not be regarded as absolute recommendations but as a set of patterns or design techniques that may be appropriate in a given setting.

1. Divide very long tunnels into a series of shorter tunnels. Open cuts can be used to provide visual relief and glimpses of surface landmarks. Make entrance and exit ramps occur above grade or in open cuts as much as possible (Figure 4-1).
2. Minimize curves and complex geometry.
3. Limit the number of entrances and exits and simplify their configurations.
4. Enlarge tunnel dimensions.
5. Increase light levels and utilize white or natural colored light.
6. Make interior surfaces light in value.
7. Utilize color, pattern, texture, and light to create variety and stimulation as well as to identify tunnel zones, entrances/ exits, or above grade landmarks and features.
8. Provide a clear, visible system of directional and emergency signs.

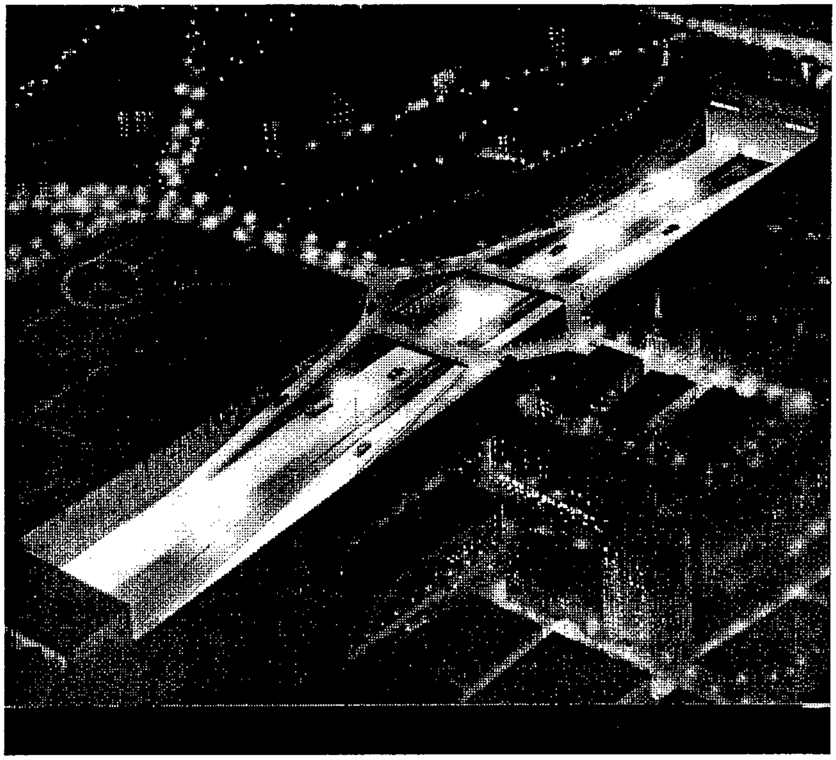

Figure 4-1: This illustration, developed for a road tunnel system in London that was never built, shows the intersection of the above grade roads with the tunnel. By using an open cut and a simple, clear configuration, drivers can maintain orientation and visualize the overall system more easily. The open cut also provides visual relief for drivers in the tunnel and a glimpse of above grade landmarks.

Design Strategies to Improve Traffic Flow and Safety in Tunnels

The potential problems identified above related to traffic flow and safety are influenced by (1) the geometry of the roadway and tunnel enclosure, (2) the portal design, and (3) the interior design elements that affect perception within the tunnel. Generally, it is desirable to minimize grade changes and curves in tunnels but this is not always possible. Graceful entrance portal transitions should occur to minimize speed reductions. Interior design elements should be designed to provide visual cues concerning speed, grade changes, and curvature.

Listed below are possible tunnel design strategies that can be used to meet the design objectives stated above. These strategies should not be regarded as absolute recommendations but as a set of patterns or design techniques that may be appropriate in a given setting.

1. Use higher levels of lighting just inside the tunnel entrance zone to make a smooth transition to the darker interior zones. This is a well-documented and widely utilized practice.

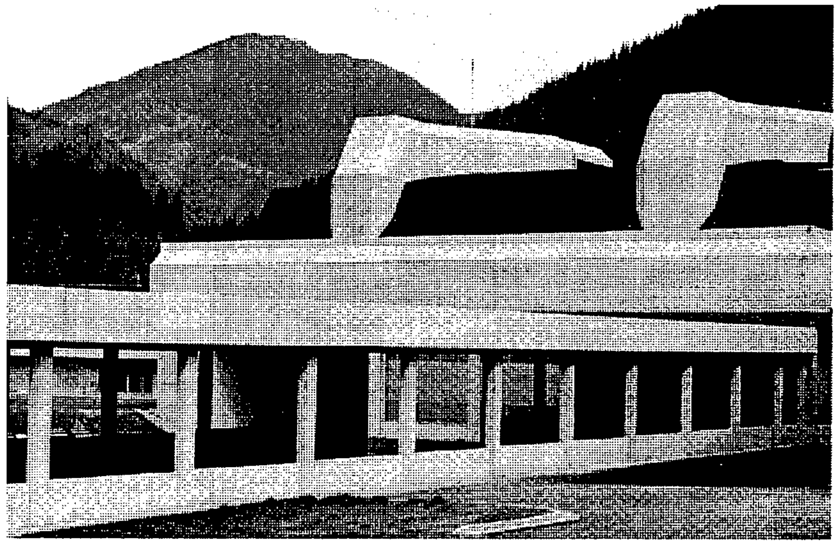

Figure 4-2: An exterior structure creates the entrance image at the 8-kilometer-long Glenhalm tunnel in Austria.

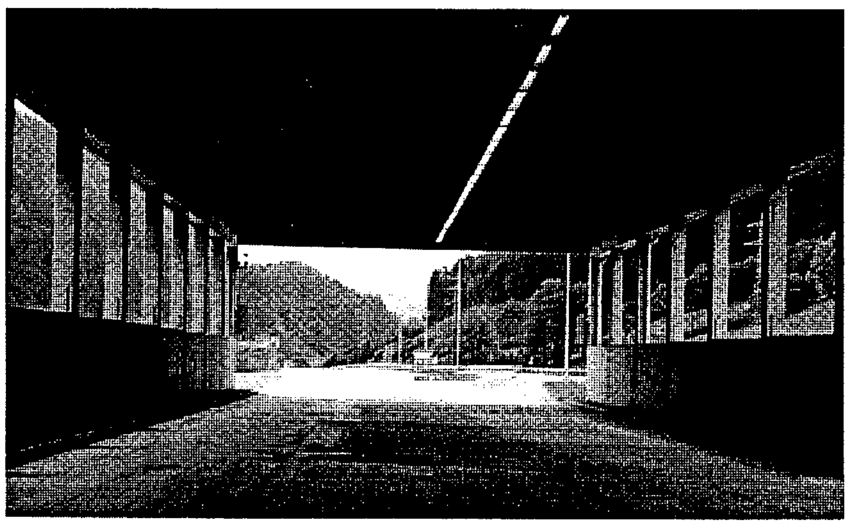

Figure 4-3: The entrance structure at the Glenhalm tunnel in Austria creates a transition in light level and in the feeling of enclosure as drivers enter the tunnel.

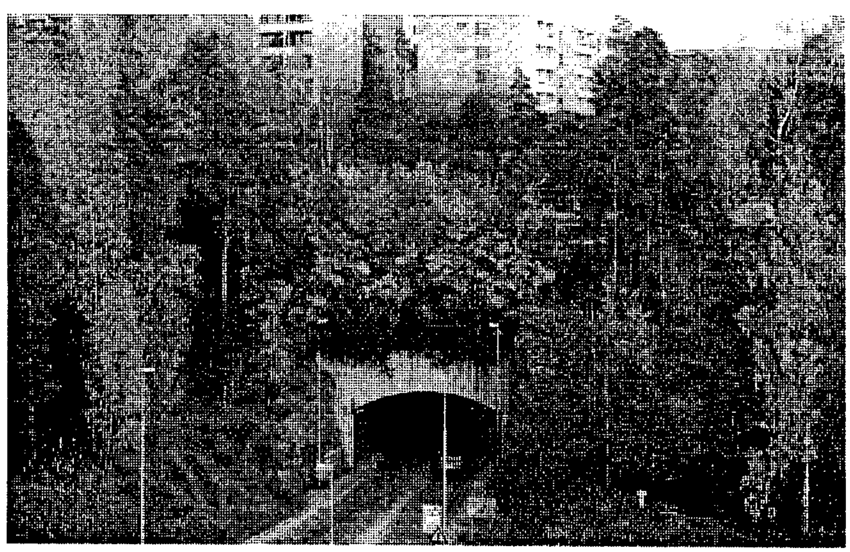

Figure 4-4: There are many distinct images in designing the entrance to a road tunnel. This Finnish tunnel is simple in design but has a positive image due to the natural surroundings.

2. Design the form of tunnel entrances to make a graceful spatial transition. Massive portal retaining walls can make an abrupt spatial change from the open road into a confined tunnel. Use of landscape elements or structures outside the portal may be useful in making the transition less abrupt (Figures 4-2 through 4-4).
3. Enlarge tunnel dimensions to improve sight lines around curves.
4. Use wall patterns with vertical and horizontal elements to give visual cues regarding speed, curvature, and grade changes.

There are very few examples of interior design in tunnels that are clearly intended to give the driver visual cues to improve safety and traffic flow, however, some designs may inadvertently have this effect. For example, simple geometric patterns found on the walls of several newer European tunnels would serve this purpose (see Figure 4-5). The use of any colors or geometric patterns on tunnel walls must be carefully evaluated to avoid creating a distraction for the driver.

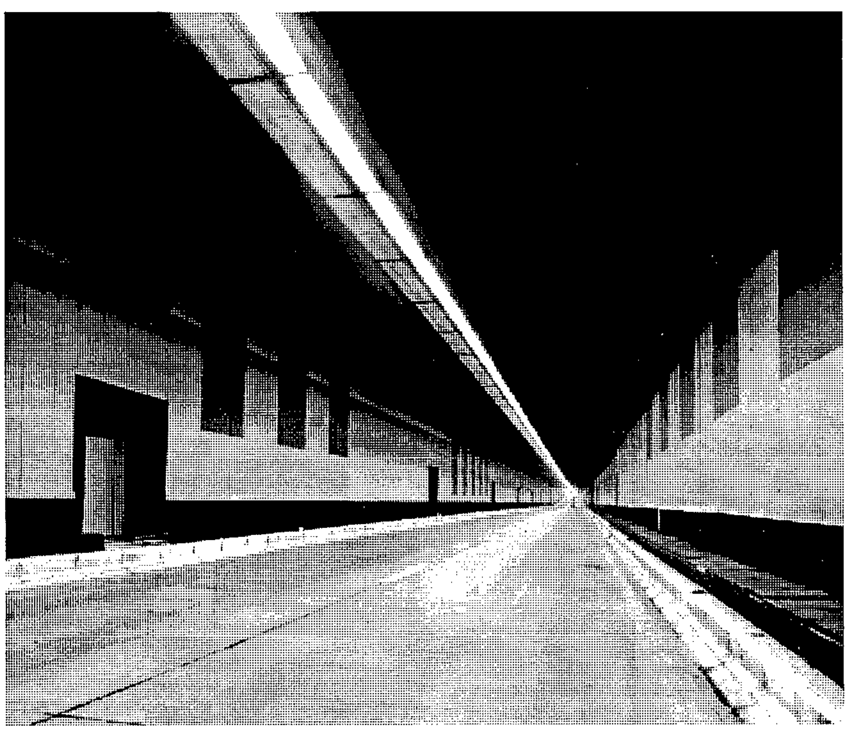

Figure 4-5: In this Belgian tunnel, walls are colored yellow with dark geometric patterns. Several concepts for geometric design on tunnel walls have been proposed to stimulate and orient drivers in tunnels.

5. Case Study: The Stockholm Ring Road

In Stockholm, Sweden, a ring road encircling the center of the city is in the design stage. An existing above ground highway forms the western quarter of the ring. The proposed project includes the remaining three quarters of the circle which totals approximately 12 kilometers of new roadway. Nearly all of this 12-kilometer roadway is to be underground in a pair of three-lane tunnels mostly in granite. The eastern section of the tunnel passes beneath the water and there are three short sections where the roadway emerges above grade. There are numerous entrance and exit ramps throughout the system.

This proposed underground ring road presents problems similar to all road tunnel design, but its size and complexity heighten concerns over certain issues such as orientation, monotony, and the image created of the city. To address these problems, the system planners held a competition between three Swedish design firms. The final design selected for development (by White Coordinator of Stockholm) introduced a number of innovations intended to alleviate some of the major psychological concerns (Figure 3).

One main attribute of the proposed design is a light-colored, uncluttered, arched ceiling in the tunnel. This lightness alleviates the dark, oppressive feeling found in most tunnels. In addition, a light ceiling makes the space feel like it has greater height. The designer's intention to use full spectrum lights could further create the illusion of a skylight above. The exposed rock walls add texture and express the natural structure.

The other notable concept in this design is the creation of large underground rooms periodically near entrance and exit ramps. These are intended to create variety driving through the system while improving sightlines for merging and exit ramps. The large rooms also provide spatial relief and a sense of location within the system.

Most of the design concepts applied to the Stockholm Ring Road address the more subjective issues of image. So far, the

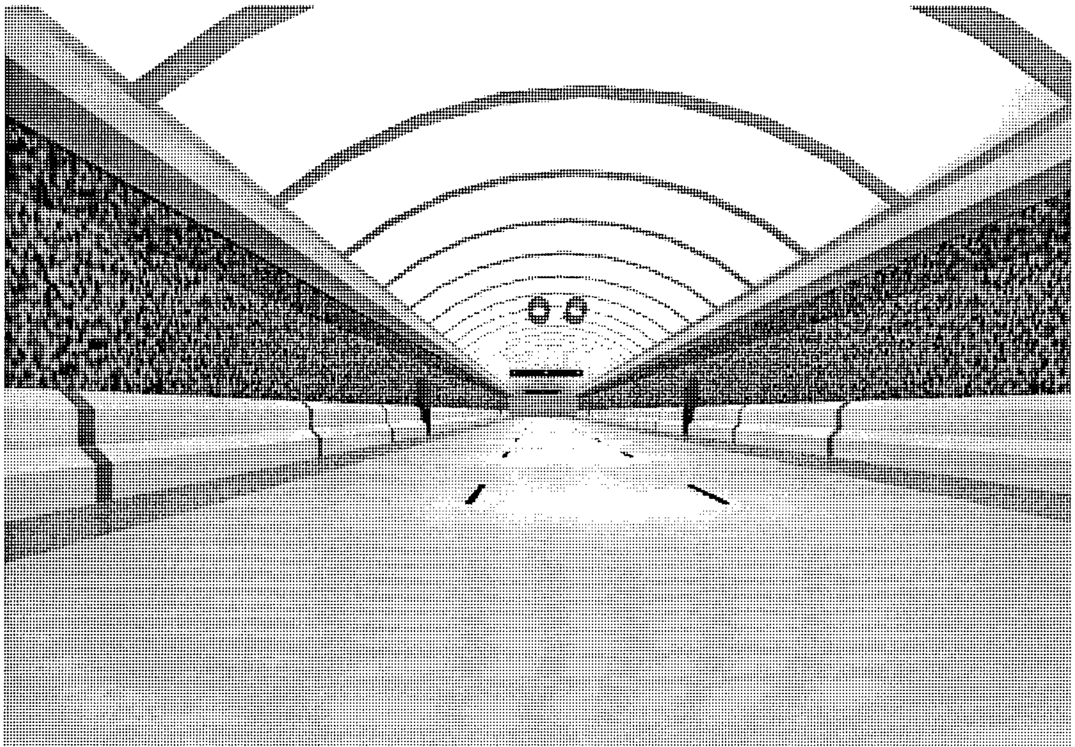

Figure 5-1: The proposed interior design for the 12-kilometer-long Stockholm Ring Road tunnel includes a light-colored ceiling and exposed granite walls.

design does not consciously attempt to use interior elements to give drivers visual cues regarding speed, curves, and grade changes. This may prove to be necessary as the design is developed, however, since the system includes some very complex entrance and exit ramps with significant curvature and grade changes.

6. Research Questions

In long urban tunnel systems such as the Stockholm ring road as well as the Boston Central Artery tunnel, designers are sensitive to many of the problems described previously. However, there is relatively little research or experience with innovative designs to inform them.

Some of the key questions that arise in the design process are:

1. Is a light-colored, high ceiling with sufficient lighting likely to alleviate feelings of darkness and claustrophobia in long tunnels?
2. How can a light-colored, ceiling be properly maintained?
3. How long can people drive in a tunnel before they begin to feel fatigue and the effects of a monotonous environment?

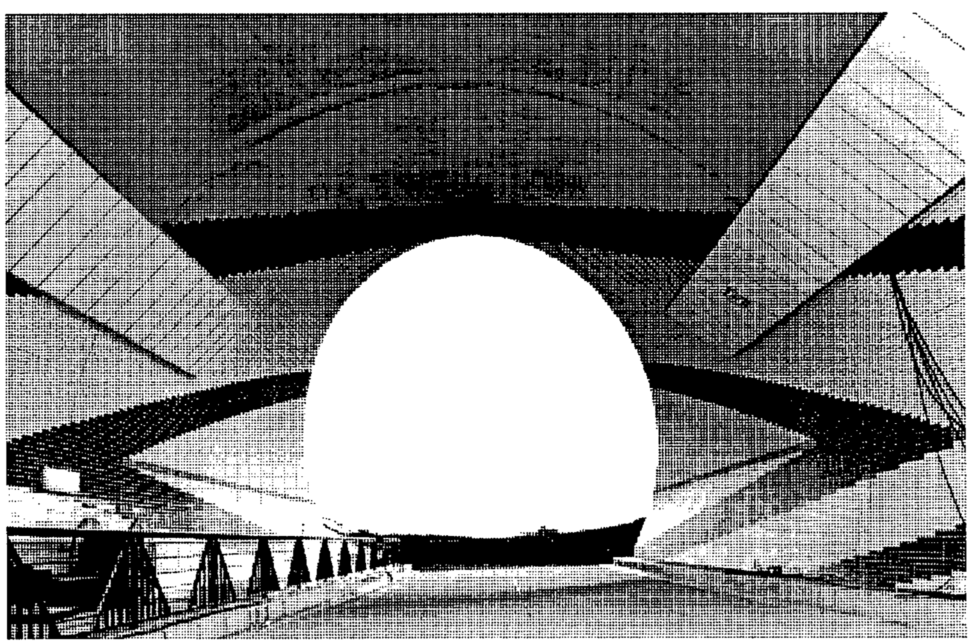

Figure 6-1: Creating a stimulating interior design is seldom attempted road tunnels. This Japanese tunnel is an exception, however it raises questions over whether a dramatic design may be distracting to the driver.

4. Do design solutions such as changes in spatial volume or interior design elements provide variety and stimulation in a long tunnel?
5. What lines, patterns, colors, and images are desirable and which are distracting to the driver?
6. Designers have experimented with many interior design concepts for road tunnels. The intention of some of the designs are:
   - to alleviate boredom with variety and stimulation
   - to maintain a sense of direction (NSEW)
   - to maintain a sense of depth (vertical/horizontal position)
   - to identify major tunnels (south-yellow, west-blue, etc.)
   - to identify exits and emergency features
   - to provide pattern and texture that informs the driver about speed, motion, curvature
   - to reflect position in tunnel with abstract patterns
   - to identify specific landmarks or districts above grade

Seldom have these concepts been evaluated, so the critical research question is whether or not they work. Some of these design issues are in the realm of subjective, aesthetic judgement, but there are many questions that lend themselves to more systematic study of driver's perceptions and behavior.

7. Research Approach

The goal of an ongoing research project at the University of Minnesota is to investigate how interior design elements (specifically geometric patterns on walls) can be used to improve the perception of curves, speed, and grade changes in a tunnel enclosure. A computer simulation of an actual tunnel has been developed and drive-through animations have been created to develop hypotheses of design approaches worthy of more detailed evaluation. Then the computer models will be imported into an interactive driving simulator and the reactions of subjects will be recorded to assess the impact of design changes on driver behavior.

The Lowry Hill Tunnel in Minneapolis, Minnesota, USA was selected for the simulation. It consists of two separated three-lane roadways with minimal shoulders. The tunnel is 457 meters long (1500 feet) with a straight section that is 244 meters long (800 feet) and a curving section that is 213 meters long (700 feet). The vertical drop in the tunnel is approximately 9.1 meters (30 feet) resulting in a slope of two percent. This tunnel presents some of the problems cited above with noticeable traffic speed reductions at entrances and speed changes in response to the grade change and curvature. The illumination is not very high and the interior walls and ceiling are yellow tile. Consequently, the tunnel has no interior design patterns that inform the driver except for the very subtle texture of the tiles.

Phase One: Creating models and drive-through simulations

A model of the Lowry Hill Tunnel was created on an Apple MacIntosh computer using UpFront (a 3-D modeling program). The walls of the tunnel consist of a gridwork of panels that can be selected in various groupings so that different color patterns can be applied. The model can be viewed in several ways:

- A driving path is created in UpFront and a Quicktime movie is constructed. This can be viewed on the screen or can be converted to videotape for viewing.

- A more detailed rendering can be created using Stratavision StudioPro which can also be converted to videotape.
- The model can be converted so that it can be used with the Silicon Graphics computer system in the Human Factors Laboratory. It can then be experienced interactively. The subject can drive through the tunnel using a mouse while watching the computer screen. In this case, speed, braking and steering are in the user's control.

A series of wall patterns were developed for the Lowry Hill tunnel to test the impact of vertical, horizontal, and combined vertical and horizontal elements (see Figures 1 through 4). In each case, a number of variations in pattern size, color, and contrast were explored. The following observations were made based on viewing computer drive-through simulations as well as driving through the model interactively using a mouse:

- The pattern with vertical elements alone gives cues regarding speed and wall curvature (Figure 7-1). Unless, the contrast between colors is very subtle, this pattern can seem particularly distracting. However, since it makes the driver more aware of speed, a vertical pattern might be used to influence drivers to diminish their speed.
- The pattern with horizontal elements alone appears to give visual cues regarding the grade change in the road (Figure 7-2). In the computer simulations, the broad horizontal stripes give a clear sense of the sloping roadway in the straight section of the tunnel, but the pattern appears distracting and more difficult to read in the curved section.
- The two-color grid pattern in Figure 7-3 combines vertical and horizontal elements. It was assumed that the visual cues provided by both would be realized. However, it appears that the arrangement of the pattern as well as color value and hue choices can make a great difference in whether the driver reads the horizontal and vertical elements in the pattern. Instead of creating clear horizontal and vertical lines, the two-color grid in Figure 3 tends to break up the lines so the eye sees the overall pattern but not the lines that extend through the pattern.
- The four-color grid pattern in Figure 7-4 also combines vertical and horizontal elements. The four colors are selected to create changing colors in one direction and changing

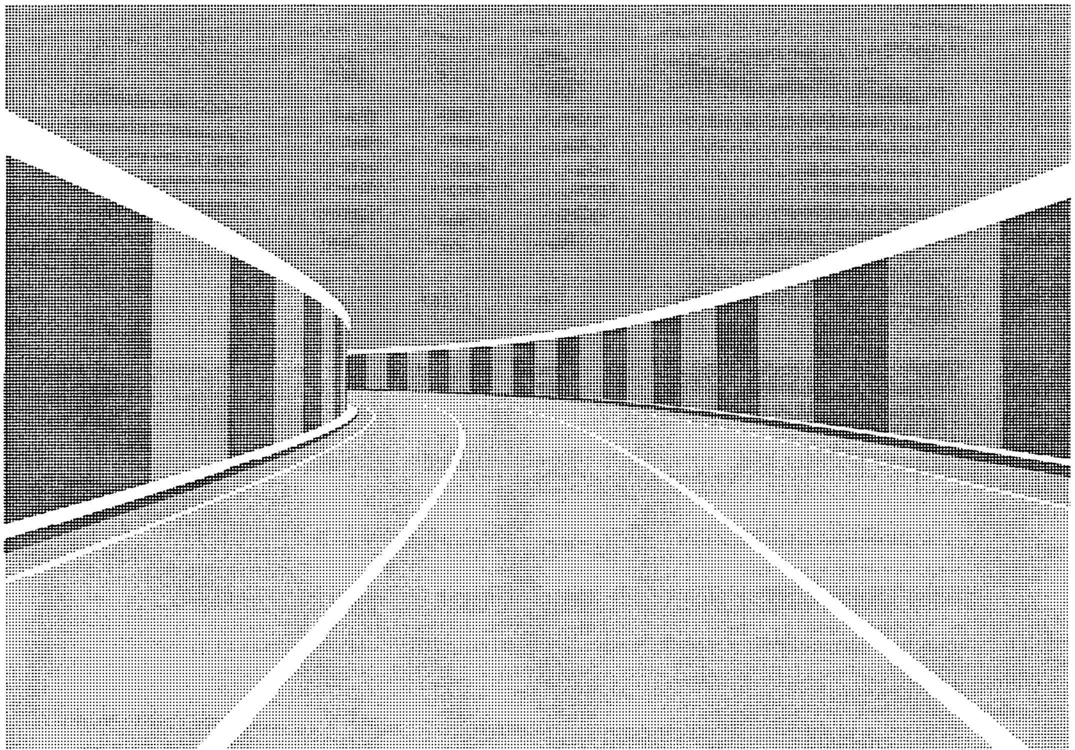

Figure 7-1: Geometric tunnel wall patterns with vertical elements provide visual cues that appear to aid in the perception of speed and curves.

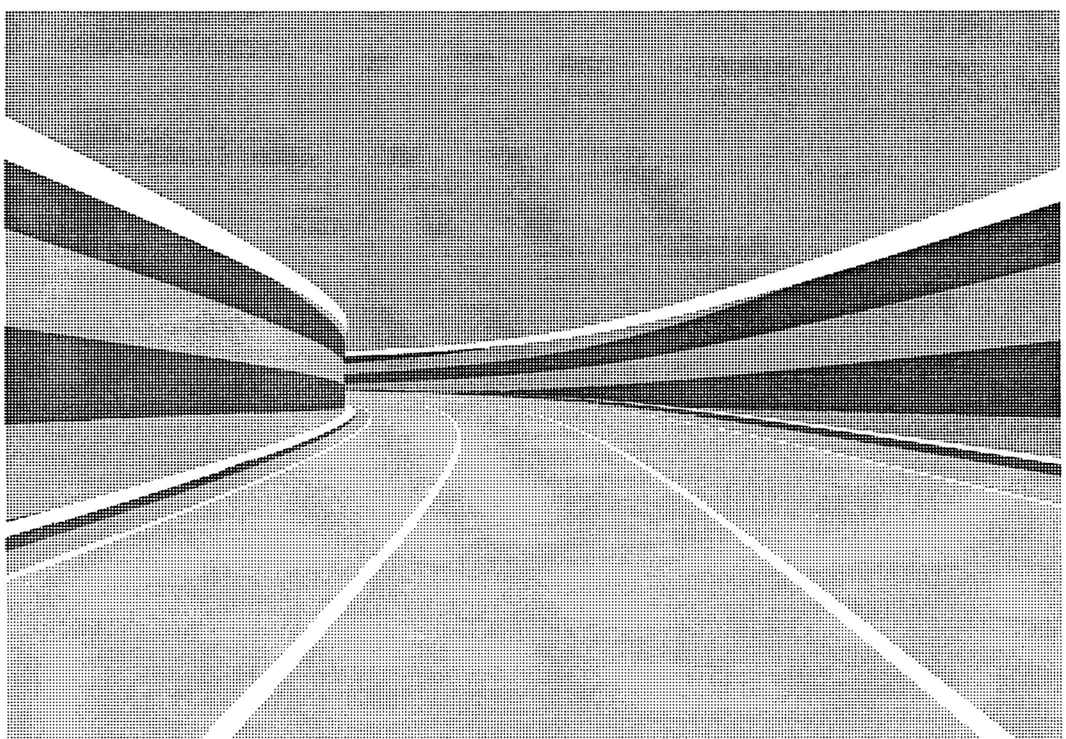

Figure 7-2: Geometric tunnel wall patterns with horizontal elements provide visual cues that appear to aid in the perception of grade changes.

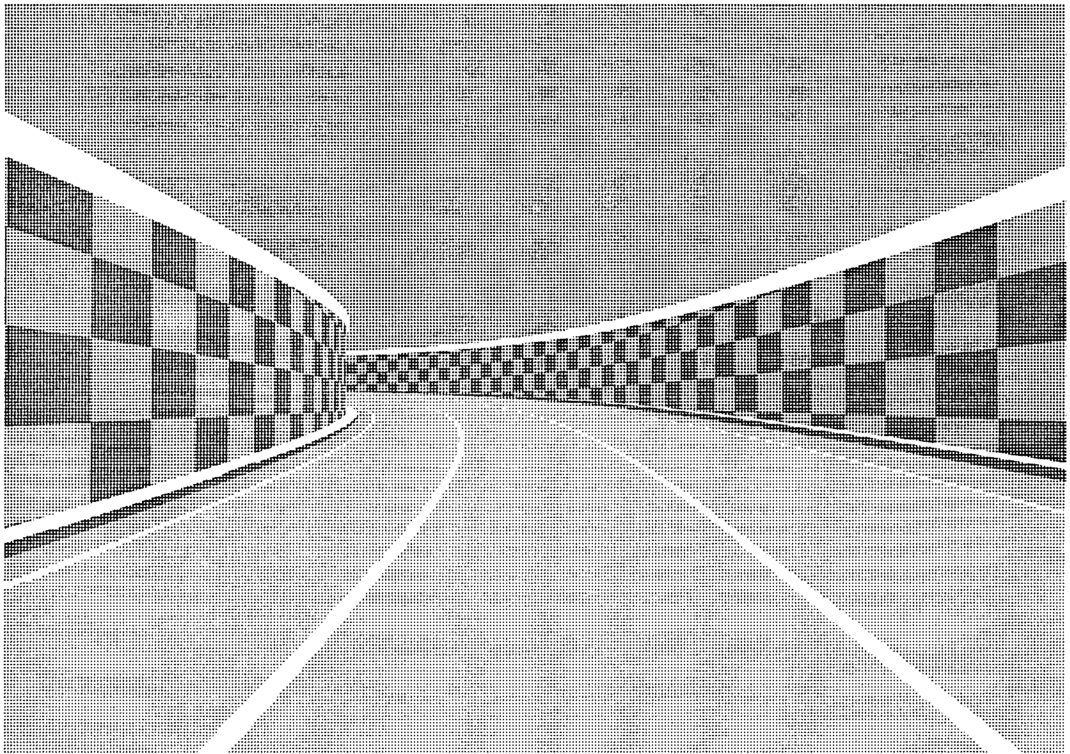

Figure 7-3: This two-color grid pattern provides some visual cues with both horizontal and vertical elements. However, the lines do not read as continuous with this pattern.

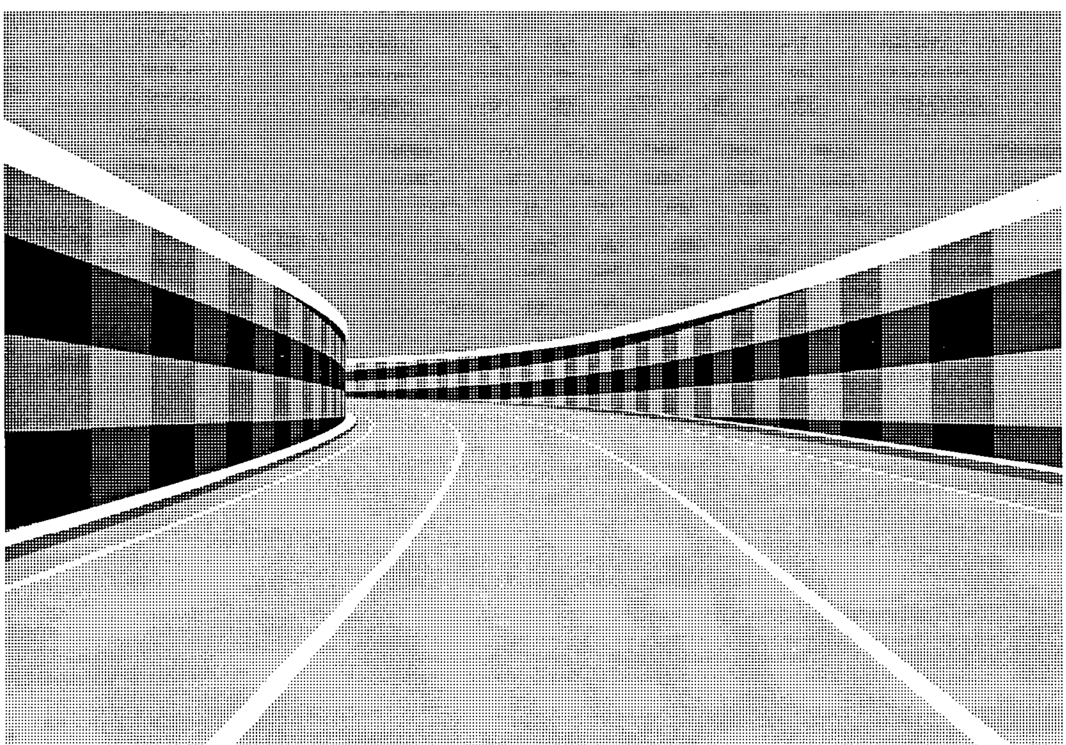

Figure 7-4: This four-color grid pattern incorporates both horizontal and vertical elements. In this case the lines do read as continuous and provides visual cues are provided for speed, curvature, and grade changes in the tunnel.

values in the other direction. Unlike the grid in Figure 3, the four-color grid in Figure 4 emphasizes the continuing horizontal and vertical line elements.

It must be emphasized that these are simply my observations and will be tested with subjects in the second phase of the research.

Phase Two: Testing subjects using the driving simulator

In phase two of the research, the model will be projected inside of the wrap-around driving simulator at the Human Factors Research Lab at the University of Minnesota. The basic cases that were evaluated in phase one will be refined and the preliminary observations will be compared to actual subject's reactions. The last phase of the research will afford the opportunity to record differences in speed and other driver responses to different design parameters.

While the simple cases illustrated in Figures 7-1 through 7-4 may suggest the use of a four-color grid for all situations, there may be greater benefits in using different patterns to denote different conditions. A simple example would be using vertical elements on road segments with curves and horizontal ones where grade changes occur. The size and spacing of elements in the patterns could be adjusted to influence drivers to reduce speed or possibly to simply make them more alert. Changes in color and contrast could also be used in this manner. Further assessment of the scale, color and contrast of pattern elements will be included in the research.

Additional Observations and Comments

In addition to giving drivers information about the roadway, varying patterns of light, color, and shape could also help alleviate two of the potential problems in long tunnel systems: (1) a monotonous visual environment, and (2) lack of orientation which affects the driver's connection to the surface and image of the city.

From an economic point of view, the design of a tunnel may influence the acceptability and success of the tunnel. In most cases, long tunnels are the shortest or possibly the only way to travel beneath a body of water or through a mountain, and they have few if any additional entrances or exits. In long urban tunnels, however, such as the proposed Stockholm Ring Road, there may be numerous entrances and exits, and drivers have other route choices that are more familiar and will be less expensive if tolls are charged in the tunnels.

Regardless of tunnel length, the interior and exterior design of the tunnel is important. The design becomes even more significant as tunnel length and complexity increase. These design issues have the danger of becoming lost or regarded as unimportant compared to other practical concerns. Yet, similar to many public spaces, aesthetic qualities are also important in roadway design, even in a mundane tunnel environment. The interior design of road tunnels is relatively unexplored and presents a new challenge to designers and researchers.

Of course, the potential influence of design on driver behavior is not limited to tunnels. Numerous roadway settings that include retaining walls and other architectural or landscape elements lend themselves to exploring these issues. Situations where influencing drivers to reduce speed such as a freeway entering downtown or a work zone could benefit greatly from this type of design approach.

A final observation related to this type of research is that there is great value in seeing roadway designs in motion by using computer simulations. Unlike spaces in buildings that are designed and seen in various static positions, roadways and tunnels are only seen in motion. When the designer or researcher observes these environments at normal driving speed, design judgements and research hypotheses are likely to be influenced considerably.

Appendix A: Psychological and Physiological Effects of People in Underground Space

This appendix is included because many of the design issues in road tunnels are related to underground space in general. This material is the basis for many of the problems, strategies, and hypotheses identified in the road tunnel project. This material was originally published in Underground Space Design *(Carmody and Sterling, 1993).*

There are numerous practical benefits to utilizing the underground for a variety of purposes. For uses such as storage, utility infrastructure, or transportation tunnels, the involvement of people in the space is relatively low and few concerns are raised. However, when underground space is to be utilized for functions that involve human occupancy, initial reactions are often negative and a wide range of concerns and questions are raised. The broad fundamental question is: "What are the psychological and physiological effects on people utilizing underground space?" A related question is: "If there are negative effects in some cases, what design strategies can be employed to alleviate these concerns and create a positive, healthy environment?"

The purpose of this section is to identify the potential psychological and physiological problems related to placing people in underground environments. Information is drawn from two sources: (1) the images of the underground that seem to be rooted in history, culture, language, and possibly the subconscious, and (2) the actual experience of people in underground or other analogous enclosed environments. These sources combine to produce a list of potential problems to overcome. Also noted at the end of the section are the mitigating factors that influence the impact of these problems as well as an identification of offsetting positive associations with the underground.

THE IMAGE OF THE UNDERGROUND

In spite of the usually well-lighted and well-ventilated examples of modern subsurface environments, the idea of the underground seems to provoke some powerful images and associations from the past. Natural caves that served as shelter to primitive humans are dark, somewhat cold places with humid, stale air. The darkness itself creates a feeling of mystery and fear of the unknown. In the book *Labyrinths of Iron,* Benson Bobrick (1981) documents the history of tunnel construction, noting the extremely dangerous activities done under the most dire conditions of foul air, wetness, and darkness. In tunnels and mines in particular, fear of entrapment is a common association. Other manmade underground structures such as catacombs, tombs, vaults, basements, and dungeons were places of enslavement, incarceration, or burial.

Paradoxically, the underground in its role as shelter also evokes the more positive associations with safety, security, and protection. The image of Mother Earth as a source of fertility and life is powerful, and yet the space within the earth is usually envisioned as a lifeless and static environment. The mystery of a dark cave inspires fear but also a sense of adventure.

These basic associations are both reflected in and enhanced by the use of underground imagery in literature, religion, language, and psychology. In *The Life Below the Ground,* Wendy Lesser (1987) explores the underground as a metaphor in literature. She points out that the underground has always been only partially visible and partially accessible to people, in spite of the access provided by continuing technological advances. She continues:

> *What this indeterminacy means is that the underground has always been situated oddly between the visible and the invisible—between that which one can see and touch in one's normal life, and that which one must accept on faith.*
>
> *This may explain, in part, why the real underground . . . has given rise to so many fictional or imaginary undergrounds. There was, to begin with, Hades—that is, the imaginary underground is first of all the locus of death and rebirth, the place where dead souls go to be washed of their memories and returned to life on earth. In this sense, the underground is both place of origin and place of final rest. From this land of the shades developed the idea of the Christian hell—no longer the abode of the undifferentiated dead, but a place of eternal punishment for the damned alone. The notion of the underworld has always held something of mystery and terror for the living, but with Christianity the subterranean began to be equated with evil— a connotation which carries through to the present. The word "underground" is associated with poverty, with criminal activity, with the socially*

> *unacceptable. Even when a group purposely describes itself in this way (as do certain political or artistic movements), the choice signifies a rejection of the conventional notion of good, an adherence to the opposite of the accepted political code or aesthetic standard (Lesser 1987).*

This predominantly negative imagery associated with the underground is based on the true conditions in caves and more primitive manmade spaces below grade, combined with the power of the underground metaphor for the mysterious and unknown. In the relatively recent past, it has become technologically possible to provide artificial illumination and mechanical ventilation that contradict the cave-like images of dark humid spaces with stale air. In many respects, underground environments have become quite similar to modern above-grade environments that are essentially artificial. In spite of solving these technical problems of providing light and air, however, other aspects of negative underground imagery persist—in particular, the lack of connection to the natural world.

In the recent book, *Notes on the Underground*, Rosalind Williams (1990) explores the broad issue of people making the century-long transition from a fundamentally natural environment to a technologically dominated environment present in cities today and likely to be developed to a greater extent in the future. She sees the underground (both in reality and in literature) as an ideal model of a completely technological environment.

> *. . . since the nineteenth century, narratives about underground worlds have provided a prophetic view into our environmental future. Subterranean surroundings, whether real or imaginary, furnish a model of an artificial environment from which nature has been effectively banished. Human beings who live underground must use mechanical devices to provide the necessities of life: food, light, even air. Nature provides only space. The underworld setting therefore takes to an extreme the displacement of the natural environment by a technological one. It hypothesizes human life in a manufactured world.*

The exclusion of nature is the key element of this model:

> *. . . the defining characteristic of the subterranean environment is the exclusion of nature—of biological diversity, of seasons, of plants, of the sun and the stars. The subterranean*

laboratory takes to an extreme the ecological simplification of modern cities . . .

While Williams acknowledges that there are other completely artificial environments such as spacecraft, and that modern cities are becoming largely enclosed artificial environments as well, she still sees the underground as the ultimate model of a technological environment with its particularly powerful psychological associations.

Unlike the mine, the spaceship fails to convey a sense of permanent enclosure in a finite world. Furthermore, because of the indeterminacy of the interstellar void, space travel lacks the verticality that gives the underworld its unique power in the human imagination.

Stories of descent into the underworld are so ancient and universal that their fundamental structure, the opposition of surface and depth, may well be rooted in the structure of the human brain. The congruence may be explained by the Freudian hypothesis of an Oedipal experience that splits human beings into conscious and unconscious selves, or by Jungian hypothesis of a collective subconscious. In any case, the metaphor of depth is a primary category of human thought.

It is the combination of enclosure and verticality— a combination not found either in cities or spaceships—that gives the image of an underworld its unique power as a model of a technological environment. If we imagine going underground, we not only imagine an environment where organic nature is largely absent; we also retrace a journey that is one of the most enduring and powerful cultural traditions of humankind, a metaphorical journey of discovery through descent below the surface (Williams 1990).

It is clear from the work of Lesser and Williams that underground images and associations are rooted in the past and infuse our culture in many ways, but they also reflect some important issues about the present and future development of the built environment. These images help to form the backdrop against which problems and solutions for underground design can be formulated.

A Japanese research team has attempted to explore the basic negative imagery associated with underground space (Hane et al. 1991; Sawada and Hane 1991; Muro et al. 1990). They state:

> *Underground space is often considered unappealing, even when there are no fundamental problems. Underground places do not provide as much stimulation; thus, imagery, which would not be an issue in other environments is a consideration in underground spaces. To utilize underground space, it is necessary not only to provide such stimulation . . . but to eliminate anxiety and dissatisfaction from the negative imagery . . . that exists within deep consciousness.*

In order to determine the imagery associated with the underground, these researchers conducted a survey with both Japanese and American subjects. Respondents selected adjectives from a list that conveyed the images of comfort, discomfort, and the underground. The words selected for underground imagery by people in both countries were mostly words that conveyed images of discomfort, although not all words reflecting discomfort were chosen for underground as well. Commonly selected words in both groups were *fear*, *uneasiness*, and *timidity*. Americans used *anxiety* and *dejection* more often than the Japanese to describe the underground, but they also associated the positive word *comfort* more often as well. Both Japanese and American subjects used the words *expectancy* and *anticipation* to reflect underground imagery, and these words also are associated with comfort. The authors suggest that designs intended to enhance these more positive associations may be a means of reducing the negative imagery of underground space. They also note that the similarity between Japanese and American responses suggests that design approaches and guidelines developed in one country can be applied in another.

ACTUAL EXPERIENCE IN UNDERGROUND BUILDINGS

While underground space is utilized all over the world and for almost every human activity, relatively little research exists on the responses of people to these environments. Some researchers have attempted to summarize the limited existing literature (Wise and Wise 1984; Carmody and Sterling 1983, 1987; Fritzell and Ranhagen 1980). These and other researchers have then drawn from many related sources of information to hypothesize the pertinent psychological issues in underground buildings (Paulus 1976). Of the few actual studies of people in underground settings, the responses are predominantly, although not entirely, negative.

Experience in Europe

Underground factories opened in Sweden in 1946 resulted in negative occupant attitudes as well as frequent reports of headaches and fatigue. A comparison of underground and conventional facilities revealed that underground workers complained much more of headaches, fatigue, eye ache, nervousness, and insomnia; however, the incidence of absenteeism was only slightly higher. After becoming accustomed to the underground conditions, absenteeism decreased to the same level as found in the above-grade facility. A blood examination revealed no significant difference between the two groups. While it was concluded that there was no proof of negative physiological effects underground, negative attitudes persisted. In 1958 a follow-up investigation revealed that the negative attitudes associated with working underground had practically disappeared. Moreover, blood tests on 100 workers who had been in the underground facility for eight years proved normal. According to researchers, however, "the psychological atmosphere remained sensitive" (Holister 1968).

In another study of Swedish workers in underground factories, there were initial complaints of fatigue, headache, impaired vision, and general depression. When inadequate lighting, ventilation, and inappropriate color schemes were improved, however, the complaints stopped (Holister 1968). Holister also describes a study of London subway workers showing that they had no higher incidence of absenteeism or any physical or mental problems caused by working underground.

In the Scandinavian countries, extensive rock caverns have been constructed in the past 20 years to relieve land use pressures and to provide civil defense facilities. In many cases these caverns are then utilized for community recreational functions such as swimming pools and gymnasiums, as well as art museums and theaters. Office and meeting spaces accompany these other functions, and as noted above, there is a history of placing some factories underground. In a review of Finnish underground facilities, Jaakko Ylinen (1989) writes of several factors that appear to affect occupant satisfaction:

> *Dissatisfaction is more common in offices or control rooms than factories or department stores, where contacts with other people, the changing surroundings, and spaciousness compensate for the lack of windows. Isolated and remote work stations should be avoided in underground spaces . . . strict control or restriction*

> *of movement in underground spaces is extremely harmful . . . It has been observed that the lack of windows in underground spaces makes the psychological atmosphere susceptible to disturbances. People using such a space often feel that something is missing; consequently, they tend to imagine that what the space lacks is perhaps more significant than it really is. This phenomenon manifests itself in various expressions of dissatisfaction directed at the environmental conditions . . . For example, an accusing finger is often pointed at the air-conditioning system, even when it is functioning properly.*

It should be noted that Scandinavian underground spaces are generally quite brightly lighted and well ventilated, compared with similar facilities elsewhere in the world.

Experience in the United States

Robert Sommer (1974) conducted a series of interviews with employees in underground offices and noted that major complaints included stuffiness and stale air, lack of change and stimulation, and the unnaturalness of being underground all day. The interviews revealed some strong opinions and images.

> *"I come out like a mole at lunchtime. It is more dull here. Time loses meaning. I have that basement feeling, burrowed in for the day. There is a lack of any buoyancy and change."*
>
> *"I get claustrophobia, I need to get out to see sunshine. I am depressed and go out whenever possible. The basement has the connotation of storage."*
>
> *"I am depressed when I get home. I have a much lower efficiency here . . . There is a stifling atmosphere, the stagnant air, the noise, the telephone ringing. It is especially bad in winter—it's dark when I come in and dark when I leave."*
>
> *"The lack of windows creates more tension. It is relaxing to look out a window for a few seconds. Artificial light, no matter how good, is less good than natural light."*

Sommer indicates that there were other employees who were less negative about working underground and appeared to have accepted their surroundings, but no one was enthusiastic. It should be noted that the subjects interviewed by Sommer did relatively boring, repetitive work and the underground spaces apparently lacked any significant amenities such as high quality furnishings, finishes, or lighting.

A systematic survey of workers in several types of office environments at the University of Minnesota revealed remarkably negative reactions in underground space (Hollon et al. 1980). Workers in the completely underground building had lower levels of satisfaction and higher ratings of anxiety, depression, and hostility than in three other settings—the basement of an above-grade building, an above-grade windowless setting, and an above-grade setting with windows. Adjectives most associated with the underground spaces were "unpleasant, dangerous, musty, dark, smothering, unfriendly, gloomy, and isolating." By contrast, the adjectives least associated with the underground were "relaxing, attractive, open, interesting, cheerful, warm, inviting, stimulating, secure, and silent."

While the Hollon et al. study appears to reveal a significant negative bias toward underground environments, even in contrast to other windowless spaces, there are a number of mitigating factors which raise questions over the ability to generalize such a study. The underground office setting was overcrowded, and the areas selected for study had virtually no amenities such as daylight and view, which were present in much of the rest of the building. The authors noted that the most frequent complaints about the underground were poor air quality and ventilation, high humidity, and poor temperature control. While these problems evoke associations with a more primitive underground cavern, they are not really intrinsic to modern underground buildings. Similar problems exist in enclosed above-grade buildings and can be resolved through proper design. In fact, air quality problems have been identified and resolved in the underground building in subsequent years (Sterling and Carmody 1990).

In contrast to these relatively negative responses to underground space, a study of workers in deep underground caverns in Kansas City, Missouri revealed a generally favorable attitude toward their environment (Hughey and Tye 1983). Unlike more typical basement space near the surface, the underground developments in Kansas City are in limestone mines at depths up to 50 meters that are entered through tunnels. Over 2 million square meters of this space is used for offices, manufacturing, and storage. In five different mined developments, 312 people were surveyed. They rated the underground environment as safe and efficient, viewed it as comparable to above-grade settings, and positively evaluated the temperature and humidity conditions. Workers were neutral with respect to overall ratings of their work areas, lighting, and ventilation. While some workers cited the conventional complaints about underground settings (i.e., no view and sunlight, poor ventilation), others found offsetting positive attributes such as a constant, pleasant temperature and being in a novel work environment with features such as exposed rock walls. It should be noted that the vast majority of the space in the Kansas City underground lacks any special amenities such as high quality finishes, furnishings, or lighting, and the air quality is not always particularly good due to the extensive truck traffic within the mines.

Experience in China

In the People's Republic of China, networks of tunnels and caverns have been constructed particularly under major cities for civil defense purposes. In recent years these spaces have been utilized for various manufacturing, storage, and community recreational purposes (Hou and Su 1988). Compared to environmental standards found in North America, Europe, and Japan, these underground spaces in China are poorly ventilated and lighted. There are few amenities and in many cases the tunnels are low and cramped. Recently a survey was conducted of workers in several underground settings in Shanghai (Su and Peng 1990). The researchers placed a number of concerns that emerged from the survey into three categories: the entrance, the underground working environment, and concerns for health and safety. Long dark tunnel entrances reinforced negative feelings, and artificial windows to improve the tunnel were disliked. Generally, most people disliked working underground and were unsatisfied with their jobs. They wished for sunlight and greenery and noticed the unusual smells underground. Most workers feared illness from the conditions and expressed concerns over their safety in fire, flood, earthquake, or structural collapse. In potential emergencies, they feared losing their way and being unable to escape. Many of these concerns seem to reflect the relatively unsafe and substandard conditions often found in Chinese underground spaces.

Experience in Japan

Severe land use pressures in Japan have led to an intense interest in extensive underground development in recent years. Researchers have begun to conduct surveys to attempt to identify the underlying psychological problems in underground work environments (Nishi et al. 1990; Wada and Sukugawa 1990). Nishi et al. compared the attitudes of above- and below-grade workers toward various aspects of underground environments. There was no significant difference between the two groups with regard to disaster prevention and safety in the underground—both were neutral. With regard to other issues, however, there was a notable difference in the attitudes of above- and below-grade workers toward underground space. More aboveground workers felt that an underground work place would present a hindrance to achieving a good interior environment, and more felt they would be extremely burdened psychologically by working underground. A remarkable 60 to 85 percent of underground workers approved of working below grade while only 25 percent of the aboveground workers approved. This study reflects the inherently negative attitudes about underground space that are based on images and associations rather than direct experience.

Another Japanese study seems to be consistent with most of the research in actual underground settings, which indicates predominantly negative feelings about the environment (Wada and Sakugawa 1990). Workers surveyed in an underground office, subway station, shopping center, and security center reported high levels of anxiety over isolation from the outside (67 percent of those interviewed) and their physical health (50 percent). Some anxiety was expressed over mental stress (36 percent) and earthquake or fire (18 percent). The most dominant complaints were (in rank order): bad air quality, lack of knowledge about the weather, an oppressive feeling, and low ceilings (even though they were the same as comparable above-grade settings). A few of those interviewed recognized the positive benefits of a quiet environment for work; however, the majority saw no advantages. More than 70 percent of those interviewed wished to work above grade, although the authors note that the physical conditions in fact were not very good in these facilities. It is interesting to note that while these workers were negative about the underground setting, they would continue to work there if conditions in the physical environment were improved—in particular, if sunlight, plants, surrogate windows, spaciousness, and more ventilation were provided. They also included a greater willingness to work there if they were compensated financially.

Wada and Sakugawa (1990) also conducted a series of experiments in laboratory settings. The performance of workers doing a variety of tasks was compared in three settings—above grade with a window, below grade with no amenities, and below grade with various amenities such as a sunlight tracking system, plants, and video monitor. While the performance was similar in all cases at the beginning, the performance of above-grade workers improved after a rest period, indicating the relaxing, restorative effect of the window view. The amenities in underground space (beamed sunlight, plants, and video monitor) seemed to reduce fatigue, but the data were insufficient to draw definite conclusions. In the underground setting, workers performed better when they descended four stories by elevator rather than by stairs. This implies that the entrance sequence may help people understand the location of the space and may have an effect on establishing the impression of and reaction to an underground environment.

ACTUAL EXPERIENCE IN WINDOWLESS AND OTHER ANALOGOUS ENVIRONMENTS

Underground spaces share some basic characteristics with certain analogous environments (Carmody and Sterling 1990). These include completely artificial environments like space capsules, submarines, and arctic or antarctic bases. Similarities include the almost complete dependence on technology for light and air as well as a sense of enclosure and isolation from the natural environment of the surface. However, these extreme environments present significant differences in that people are confined to them 24 hours a day for periods of a few days to up to several months and in the future, possibly, years. In underground environments, people have periodic access to the surface and at most spend eight hours a day in the facility. Another key difference is that the occupants of these extreme environments are there by choice and are motivated to accomplish a particular mission or scientific endeavor. Because of these differences, overall reactions to these environments do not seem to provide directly analogous information for underground settings. A review of literature related to these extreme environments does reveal, however, some specific design problems that are similar (i.e., enhancing spaciousness, using interior design to create stimulation, developing surrogate views, and designing artificial light to replicate characteristics of natural light).

There is one category of analogous environments—windowless buildings—that is so similar to underground space that they are sometimes treated as interchangeable. The lack of windows in buildings above and below grade seems to contribute to the majority of negative attitudes and associations (i.e., claustrophobia, lack of view, natural light, stimulation, and connection to nature). Underground buildings, however, seem to elicit an additional set of negative associations not entirely attributable to lack of windows (i.e., disorientation, coldness, high humidity, poor ventilation, lack of safety, and various cultural and status associations discussed in the previous section). Nevertheless, experience in windowless environments can enhance the overall understanding of people in underground space, but it too is relatively limited.

Several researchers have surveyed the existing literature on windowless buildings (Holister 1968; Collins 1975; Wotton 1981; Wise and Wise 1984; Heerwagon 1990). Each of these surveys is, of course, constrained by the time of the study, and in some cases the survey is selective in order to focus on particular aspects of windows in buildings. In most cases the researchers infer from the literature the multiple functions and values associated with windows in buildings. Drawing from these surveys as well as specific studies on windowless buildings, there appears to be information on people's reactions to windowless schools, offices, hospitals, and factories.

Windowless Schools

Windowless schools in the United States were constructed to provide emergency shelter as well as to reduce vandalism, glare, overheating, outside distraction, and wasted wall space (Collins 1975). In one set of studies in California, there were no significant differences between students in windowed versus windowless classrooms as measured by achievement tests, personality tests, school health records, and grades (Demos et al. 1967). A Michigan study revealed similar findings—there were no conclusive detrimental effects on students in windowless classrooms (Larson 1965). In the Larson study, teachers surprisingly were highly in favor of the windowless classrooms. In these and other studies conflicting attitudes about windows were found. In her survey of these and several other studies of windowless schools, Collins (1975) notes: "If any single conclusion is to be reached from the studies of windowless schools, it is that the absence of windows neither improves nor impairs performance. Although some students like the situation, others, possibly a majority would prefer to have windows. The most striking conclusion seems to be the absence of significant findings, either for or against."

Windowless Offices

Predominantly negative reactions to underground windowless offices were discussed in the previous section (Sommer 1974). Another notable study of windowless above-grade offices was conducted by Ruys (1970). Ninety percent of the female office workers expressed dissatisfaction with the lack of windows, and almost 50 percent thought the lack of windows negatively affected them or their work. Complaints included no daylight, poor ventilation, inability to know about the weather, inability to see out and have a view, feelings of being "cooped up," isolation and claustrophobia, and feelings of depression and tension. It should be noted that these workers were in small, often single-occupant offices with little freedom of movement. Cuttle (1983) conducted a more recent survey of 471 office workers in New Zealand and England indicating a strong preference for windows. On the other hand, in other studies the presence of windows and views was rated as a relatively unimportant factor in contributing to a good office environment (Heerwagon 1990).

Windowless Hospital Rooms

Hospital settings have yielded some useful information on the impact of windows since patients are in small spaces continuously and their physiological reactions are being monitored. Wilson (1972) compared patients in intensive care units with and without windows. Those in the windowless setting developed post-operative delirium twice as often (40 percent versus 18 percent) as those in the unit with windows. Wilson also noted an increased incidence of post-surgical depression in patients in the windowless setting. In another study of patients in post-operative recovery rooms, Ulrich (1984) found that the content of the view through the window also affected the patients' recovery time and medication needs. Patients viewing trees had more beneficial results than those viewing a brick wall.

Windowless Factories

A previous section discussed underground windowless factories in Sweden. Although negative attitudes predominated and there were frequent complaints of physical symptoms, no major physiological problems were discovered. Elsewhere, studies of workers in windowless textile factories in the United States, Austria, and the former West Germany revealed no indication of illness attributed to the windowless condition (Holister 1968).

The Functions of Windows

Wyon and Nilsson (1980) conducted a study that included occupants of windowless factories, offices, shops, and colleges in Sweden. Their attitudes toward windows were compared with those of workers in settings with windows. The underlying hypothesis of the researchers was that it is difficult for those in conventional environments with windows to analyze what it is they appreciate about the windows since they take them for granted. This hypothesis was confirmed by the attitudes toward windows expressed by these two groups. Interesting findings included the fact that people in windowless rooms were less, not more, positive toward windows compared with those in settings with windows. In windowless settings the trend is for those with the least interesting jobs to miss windows the most. In fact, the authors suggest that windows may be important in reverse proportion to job status. Remarkably, the survey found that blind people missed windows more than sighted people. The sounds of wind, rain, and activity as well as smells from outside were an important source of stimulation for them.

The research of Wyon and Nilsson (1980) led them to conclude that windows have multiple functions and effects on the indoor environment. They influence the lighting and thermal environments in several ways; they provide visual and acoustical information from the outside; they affect air quality and ventilation; and they may serve as emergency exits. Collins (1975) would classify the major window functions as providing view, stimulation, sunlight, and a sense of spaciousness. Heerwagon (1990) describes these functions as providing access to environmental information, access to sensory change, a feeling of connection to the outside world, and restoration and recovery. She further suggests that existing research on windows only probes people's conscious awareness of their obvious benefits, and that "there are good reasons to believe . . . that our response to windows may be largely unconscious and the benefits are much more profound than previously believed" (Heerwagon 1990). In any case, to design underground space effectively the broadest possible range of window attributes should be identified so that they can be provided or compensated for by design.

SUMMARY OF PROBLEMS

While the research on people in underground and windowless spaces is not conclusive, the major issues appear fairly clear and the same set of problems emerge to varying degrees in most cases. Drawing from the existing research as well as from the generally shared images and associations of the underground discussed earlier, it is possible to identify a set of potentially negative psychological and physiological effects. These are listed in the adjacent box.

While the psychological and physiological problems are listed separately, the physiological concerns (sunlight, ventilation, and humidity) all have a psychological component. Even though a building may have adequate artificial lighting, mechanical ventilation, and humidity control, these factors can still be perceived as inadequate regardless of the actual conditions.

It is interesting to note that these potentially negative effects are all related to one of three basic physical characteristics of underground buildings: (1) lack of visibility from the exterior, (2) lack of windows, and (3) being underground. Lack of visibility from the exterior causes the lack of a distinct image and the inability to find the entrance, while it contributes to a lack of spatial orientation inside the building since the overall configuration cannot be easily understood. The absence of windows causes a sense of confinement, lack of stimulation and connection to the outdoors, and lack of sunlight. The windowless nature of underground buildings also contributes to lack of spatial orientation since reference points to the exterior are missing, which is related to a fear of not being able to escape in an emergency. Although windows are often sealed in modern buildings, the lack of windows nevertheless seems to contribute to a perception of poor ventilation. Finally, simply being underground elicits associations with darkness, coldness, dampness, poor air quality, lower status, and fear of collapse or entrapment.

Although the research on people in subsurface buildings and the generally perceived characteristics of the underground result in a predominantly negative picture, there are, nevertheless, some positive associations and characteristics as well. These are a sense of security and protection, a quiet environment without distractions, and sometimes a setting that is stimulating due to its novelty and even sense of mystery and adventure.

Mitigating Factors

While the general list of problems related to people in underground space is a valid set of hypotheses on which to proceed with design solutions, it is important to recognize that a number of mitigating factors affect the importance or even the relevance of these design issues. In several of the research studies cited throughout this section, authors have identified key factors that affect the acceptability of underground space (Collins 1975; Wyon and Nilsson 1980; Wada and Sukugawa 1990). These are:

1. **The building function.** Obviously, all psychological and physiological issues are irrelevant for functions such as utilities and storage underground, whereas they are extremely important for functions that are highly people-oriented such as offices or hospital rooms. Even among the various people-oriented functions, however, there are facility types that are relatively well suited to an enclosed, windowless environment and are often intentionally built that way (i.e., theaters, museums, libraries, gymnasiums, laboratories, and manufacturing plants).
2. **Occupancy patterns and freedom of movement.** The effects of an underground environment are mitigated by the amount of time spent there. Greater concern is raised for office workers or hospital patients who have little or no freedom of movement, compared with a museum visitor or an executive who spends the day moving around.
3. **Type of activity.** The acceptability of windowless, underground space appears to be related to the type of activity. Basically, people doing boring, monotonous work seem to complain more about lack of windows than those with more stimulating activities.
4. **Social contact and stimulation by internal activity.** The inherent lack of stimulation underground is offset to some degree by social contact and dynamic activity within a space. For example, the windowless nature of a department store does not seem to bother people as much as with other functions due to the continual contact with people as well as the constant activity.

5. **Size of space.** Smaller spaces such as private offices and hospital or hotel rooms exacerbate the feelings of confinement underground. Larger, more open spaces not only are less claustrophobic but also are likely to contain more activity and stimulation.
6. **The degree to which a building is underground.** Generally, underground buildings can be classified as near surface or deep. In deeper facilities, entered through long shafts or tunnels, the negative associations with being underground are likely to be greater while the opportunities to provide amenities such as light and view through courtyards are diminished. In some cases near-surface facilities may be completely windowless and raise the full set of people-related concerns with underground space. However, near-surface buildings may also be connected to the surface in various ways (i.e., hillside exposure or sunken courtyards) that largely overcome any negative perceptions.
7. **The quality of the interior spaces.** Many of the studies about people in windowless and underground facilities have been conducted in settings with marginal conditions of lighting and ventilation with little or no attention to providing any amenities of interior design. Obviously, the level of furnishings, finishes, lighting, and other amenities will influence perceptions.
8. **Individual variation.** Most studies of people in windowless underground environments indicate a range of responses.

References and Bibliography

Part 1: References directly related to road tunnels

Amundsen, Finn H., 1992. "Driver Behaviour in Norwegian Road Tunnels," *Safety in Road and Rail Tunnels*, First International Conference, Basel, Switzerland.

Appleyard, D. and K. Lynch, 1964. *View from the Road*, MIT Press, Cambridge, MA.

Carmody, John C. and R.L. Sterling, 1993. *Underground Space Design*, Van Nostrand Reinhold Company, New York, NY.

Carmody, J. "Impact of Interior Design on Road Tunnel Safety and Driver Perception," *Second International Conference on Safety in Roads and Rail Tunnels*, Granada, Spain, 1995.

Serrano, J. M. and F. Blennemann, 1992. "Motorist Behaviour study for the Gibraltar Road Tunnel," *Tunnelling and Underground Space Technology*, Pergamon Press, Vol. 7, No. 1.

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Part 2: References related to psychological and design issues in underground facilities in general

Aksugür, E. 1979. The effect of hues of walls on the perceived magnitude of space in a room under two different light sources having different spectral distributions. *Architectural Bulletin* 4:22-47 (as cited in Kuller 1981).

Alexander, C., S. Ishikawa, and M. Silverstein, with M. Jacobson, I. Fiskdahl-King, and S. Angel. 1977. *A Pattern Language*. New York: Oxford University Press.

Ankerl, G. 1981. *Experimental Sociology of Architecture*. New York: Mouton (as cited in Tiedje 1987).

Aubree, A. 1978. Artificial lighting during the day of a deep room. Illuminating Engineering Society Conf. (as cited in Wise and Wise 1984).

Bain, B.A.
—1989. The entry experience: Preferences of the mobility-impaired. *Changing Paradigms*. Proc., Environmental Design Research Association Annual Conf., EDRA 20, North Carolina State Univ.
—1990. Approaching buildings: A conceptual model of the entry sequence. *Coming of Age*. Proc., Environmental Design Research Association Annual Conf., EDRA 21, Univ. of Illinois at Urbana-Champaign.

Barton, M., M. Spivack, and P. Powell. 1972. The effects of angle of light on the recognition and evaluation of faces. *Journal of the Illuminating Engineering Society,* April: 231-34 (as cited in Wise and Wise 1984).

Bennett, D.J. 1978. Notes on the underground. *Earth Covered Buildings and Settlements*. Conf. Proc., Ft. Worth, Tex., ed. F. Moreland. Government Printing Office, Conf-7805138-P2.

Birkerts, G. 1974. *Subterranean Urban Systems*. Industrial Development Division, Inst. of Science and Technology, Univ. of Michigan.

Birren, F. 1983. Color and psychotherapy. *Interior Design,* Dec. (as cited in Mahnke 1987).

Bitter, C., and J.F. van Ierland. 1967. Appreciation of sunlight in the home. *Proceedings of the Conference on Sunlight in Buildings*: 27-37. Rotterdam: Bouwcentrum International.

Bobrick, B. 1981. *Labyrinths of Iron*. New York: William Morrow and Company, Inc.

Boyce, P.R. 1980. *Human Factors in Lighting*. London: Applied Science Publishers.

Brill, M., S. Margulis, and E. Konar. 1983. *Using Office Design to Increase Productivity*. Buffalo Organization for Social and Technological Innovation, in association with Westinghouse Furniture Systems.

Canter, D. 1976. *Environmental Interaction*. New York: International University Press (as cited in Wise and Wise 1984).

Carlson, L. 1991. Personal communication, Aug. 14.

Carmody, J., and R. Sterling.
—1983. *Underground Building Design: Commercial and Institutional Structures.* New York: Van Nostrand Reinhold. ISBN 0-442-28746-1.
—1987. Design strategies to alleviate negative psychological and physiological effects in underground space. *Tunnelling and Underground Space Technology* 2 (1): 59-67. Pergamon Press.
—1990. Underground space on earth: Analog for a lunar base. *Proc.,Space 90, Engineering, Construction, and Operations in Space,* Albuquerque, N. Mex.

Clearwater, Y.A., and R.G. Coss. 1991. Functional aesthetics to enhance well-being in isolated and confined settings. *From Antarctica to Outer Space: Life in Isolation and Confinement.* New York: Springer-Verlag.

Cochran, C.D., and S. Urbanczyk. 1982. The effect of availability of vertical space on personal space. *Journal of Psychology* 3:137-40 (as cited in Tiedje 1987).

Collins, B. 1975. *Windows and People: A Literature Survey.* Washington, D.C.: NBS Building Science Series.

Cooper-Marcus, C. 1985. *Design Guidelines: A Bridge Between Research and Decision-Making.* Center for Environmental Design Research, Univ. of Calif., Berkeley. Report CEDR-WP08-85.

Coss, R.G., Y.A. Clearwater, C.G. Barbour, and S.R. Towers. 1989. *Functional Decor in the International Space Station: Body Orientation Cues and Picture Perception.* NASA Technical Memorandum 102242.

Cuttle, K. 1983. People and windows in work places. *Proc. Conf., People and the Physical Environment Research.* New Zealand: Ministry of Works and Development.

Dantsig, N.M., P.N. Lazareo, and M.V. Sokolov. 1967. *Ultraviolet Installations of Beneficial Action.* CIE (Commission Internationale de l'Eclairage) Publication 20: 67.

Deasy, C.M. 1985. *Designing Places for People: A Handbook on Human Behavior for Architects, Designers, and Facility Managers.* New York: Whitney Library of Design.

Degenkolb, J.G. 1981. Fire protection for underground buildings. *Underground Space* 6 (2): 93-95. Pergamon Press.

Demos, G.D., S. Davis, and F.F. Zuwaylif. 1967. Controlled physical environments. *Building Research* 4:60-62 (as cited in Collins 1975).

Doubilet, S., and T. Fisher. 1986. Hong Kong Bank. *Progressive Architecture* 3:86.

Feller, R.P., et al. 1974. Significant effect of environmental lighting on caries incidence in the cottom rat. *Proc. Society for Experimental Biology and Medicine*, 1065-68.

Fennell, D. 1988. *Investigation into the King's Cross Underground Fire*. London: The Department of Transport.

Flynn, J.E., A.W. Segil, and G.R. Steffy. 1988. *Architectural Interior Systems*. Second Edition. New York: Van Nostrand Reinhold.

Flynn, J.E., and T.J. Spencer. 1971. The effects of light source color on user impression and satisfaction. *Journal of the Illuminating Engineering Society*, April:167-79.

Fritzell, C., and U. Ranhagen. 1980. Human beings underground. *Subsurface Space*, Vol. I. Proc., Rockstore 80, Stockholm.

Gerlach, K.A. 1974. Environmental design to counter occupational boredom. *Journal of Architectural Research*, Sept. 15-19 (as cited in Wise and Wise 1984).

Gilmer, R. 1966. *Industrial Psychology*. New York: McGraw-Hill.

Gurovskiy, N.N., F.P. Kosmolinskiy, and L.N. Mel'nikov. 1986. Proyektirovaniye usloviy zhizni i raboty kosmonavtov. (Designing the Living and Working Conditions of Cosmonauts.) NASA Technical Memorandum 76497 (as cited in Wise and Rosenberg 1988).

Hane, T. 1989. Application of solar daylighting systems to underground space. *Tunnelling and Underground Space Techology* 4 (4): 465-70. Pergamon Press.

Hane, T., K. Muro, and H. Sawada. 1991. Psychological factors involved in establishing comfortable underground environments. *Urban Underground Utilization '91*, Proc. 4th Int. Conf. on Underground Space and Earth Sheltered Buildings, Tokyo, Japan.

Hashimoto, S., N. Yamaguchi, and M. Kawasaki. 1989. *Experimental Research on the Aromatheraputic Effect of Fragrances in Living Environments*. Tokyo: Institute of Technology, Shimizu Corporation.

Heerwagon, J. 1990. Windows, windowlessness and simulated view. *Coming of Age*. Proc., Environmental Design Research Association Annual Conf., EDRA 21, Univ. of Illinois of Urbana-Champaign.

Heerwagon, J., and G. Orians. 1986. Adaptations to windowlessness: A study of the use of visual decor in windowed and windowless offices. *Environment and Behavior* 8 (5): 623-39.

Holister, F.D. 1968. *A Report on the Problems of Windowless Environments*. A report to the Greater London Council. London: Hobbs the Printers, Ltd.

Hollon, S.D., P.C. Kendall, S. Norsted, and D. Watson. 1980. Psychological responses to earth sheltered, multilevel and aboveground structures with and without windows. *Underground Space* 5 (3): 171-78. Pergamon Press.

Hollwich, F. 1980. *The Influence of Ocular Light Perception on Metabolism in Man and in Animals*. New York: Springer Verlag.

Holm, W., and G. Roessler. 1972. Sunlight in dwellings. *Proc. CIE Study Group Symposium*, Varna, Bulgaria, Oct. (as cited in Collins 1975).

Hopkinson, R.G. 1967. The psychophysics of sunlighting. *Proceedings of the Conference on Sunlight in Buildings*, 13-17. Rotterdam: Bouwcentrum International.

Hopkinson, R.G., and J.B. Collins. 1970. *The Ergonomics of Lighting*. London: MacDonald Technical and Scientific.

Hou, X., and Y. Su. 1988. The urban underground space environment and human performance. *Tunnelling and Underground Space Technology* 3 (2): 193-200. Pergamon Press.

Hughey, J.B., and R.L. Tye. 1983. Psychological reactions to working underground: A study of attitudes, beliefs and valuations. *Underground Space* 8 (5-6): 381-91. Pergamon Press.

Imamoglu, V. 1986. Assessing the spaciousness of interiors. *O.D.T.U. Mimarlik Fakultesi Dergisi* 7 (2): 127-37. Bahar (as cited in Tiedje 1987).

Imamoglu, V., and T.A. Markus. 1973. The effect of window size, room proportion and window position on spaciousness evaluation of rooms. *Windows and Their Function in Architectural Design*. Proc., CIE Conference, Istanbul, Turkey.

Inui, M. 1980. Views through a window. *Daylight*: Proc., CIE Symposium, Berlin, Germany, 323-32 (as cited in Wotton 1981).

Inui, M., and Miyata. 1973. Spaciousness in interiors. *Lighting Research and Technology* 5 (2): 103-11.

Itten, J. 1970. *The Elements of Color*. New York: Van Nostrand Reinhold.

Jackson, G.J., and J.G. Holmes. 1973. Let's keep it simple - daylight design. *Light and Lighting*, Feb.: 59-60, and March: 80-82 (as cited in Collins 1975).

Kaye, S.M., and M.A. Murray. 1982. Evaluations of an architectural space as a function of variations in furniture arrangement, furniture density, and windows. *Human Factors* 24 (5): 609-18 (as cited in Wise 1985).

Keighley, E.C. 1973. Visual requirements and reduced frustration in offices - A study of multiple apertures and window area. *Journal of Building Science* 8:311-20 (as cited in Collins 1975).

Kornsand, N.J. 1980. Convention center offers fire protection design challenge. *Specifying Engineer* 43 (5): 75-80.

Krokeide, G. 1988. An introduction to luminous escape systems. *Safety in the Built Environment*, ed. J.D. Sime. London: E. and F.N. Spon.

Kuller, R.

—1980. Non-visual effects of daylight. *Proc. Symp. on Daylight: Physical, Psychological and Architectural Aspects*: 172-81. Commission International De l'Eclairage.

—1981. *Non-Visual Effects of Light and Color: Annotated Bibliography*. Stockholm: Swedish Council for Building Research.

Larson, C.T. (ed.). 1967. *The Effect of Windowless Classrooms on Elementary School Children*. Architectural Research Laboratory, Dept. of Architecture, Univ. of Michigan (as cited in Collins 1975).

Lavianna, J.E., R.H. Mattson, and F.H. Rohles. 1983. Plants as enhancers of the indoor environment. *Proc. Human Factors Society, Vol. II*, Norfolk, Va.

Les Halles: achèvement d'un projet, *Paris-Projet* n°25-26, 1985.

Lesser, W. 1987. *The Life Below the Ground: A Study of the Subterranean in Literature and History.* Boston: Faber and Faber.

Levin, H., and L. Duhl. 1984. Indoor pollution: Lighting, energy, and health. *Architectural Research.* New York: Van Nostrand Reinhold.

Lewy, A.J., et al. 1982. Bright artificial light treatment of a manic-depressive patient with a seasonal mood cycle. *American Journal of Psychiatry* 139:1496-98 (as cited in Mahnke and Mahnke 1987).

Li, K.C. 1989. Fire protection in caverns. *Rock Cavern - Hong Kong.* Proc. Seminar, Hong Kong, Dec. 8-9, 1989, eds. W.A. Malone and P.G.D. Whiteside. Institute of Mining and Metallurgy. ISBN 1 870706 14 5.

Linn, C. 1988. Lighting makes airport club, business center relaxing, inviting. *Architectural Lighting* 2 (8): 34-37.

Littlechild, B.D. 1989. Fire engineering design proposal for a large commercial complex in a cavern in Hong Kong. *Rock Cavern - Hong Kong.* Proc. Seminar, Hong Kong, Dec. 8-9, 1989, eds. W.A. Malone and P.G.D. Whiteside. Inst. of Mining and Metallurgy. ISBN 1 870706 14 5.

Longmore, J., and E. Ne'eman. 1974. The availability of sunshine and human requirements for sunlight in buildings. *Journal of Architecture Research* 3 (2).

Lynch, K. 1960. *Image of the City.* Cambridge, Mass.: MIT Press.

Maas, J.B., J.K. Jayson, and D.A. Kleiber. 1974. Effects of spectral differences in illumination on fatigue. *Journal of Applied Psychology* 59 (4): 524-26.

Mahnke, F., and R. Mahnke. 1987. *Color and Light in Manmade Environments.* New York: Van Nostrand Reinhold.

Manning, P. (ed.). 1965. *Office Design: A Study of Environment.* Liverpool, Pilkington Research Unit, Liverpool Univ. Dept. of Building Science (as cited in Collins 1975).

Markus, T.A. 1967. The significance of sunshine and view for office workers. *Proc. Conf. on Sunlight in Buildings,* 59-93. Rotterdam: Bouwcentrum International.

Mayron, L.W., J. Ott, J. Amontree, and R. Nations. 1975. Light, radiation, and dental caries. *Academic Therapy* 10 (4): 441-48.

Mayeron, L.W., J. Ott, R. Nations, and E.L. Mayron. Light, radiation, and academic behavior. *Academic Therapy* 10 (1): 33-47.

Mel'nikov, L.N. 1978. Komnaty psikhologicheskoy razgruzki (Psychological relief rooms). *Mashino stroitel* 1:33-34 (as cited in Clearwater and Coss 1989).

Menchikoff, A. 1975. La Perception des Volumes. *Psychologie,* July: 48-51 (as cited in Wise 1985).

Mori, K. 1988. Solar energy technology for use in future cities. *A New Frontier: Environments for Innovation*. Proc. Int. Symp. on Advanced Comfort Systems for the Work Environment.

Muro, K., H. Sawada, and T. Hane. 1990. Psychological issues on utilization of underground spaces. Tokyo: Institute of Technology, Shimizu Corporation.

National Fire Protection Association (NFPA). 1991. *NFPA 101 Life Safety Code.* Quincy, Mass.: National Fire Protection Association.

Ne'eman, and Hopkinson. 1970. Critical minimum acceptable window size: A study of window size and provision of a view. *Lighting Research and Technology* 2:17-27.

Neer, R.M., T. Davis, A. Walcott, S. Koski, P. Schepis, I. Taylor, L. Thorington, and R.J. Wurtman. 1971. *Nature* 229 (5282): 255-57.

Nelson, H., and H. MacLennan. 1988. *Fire Protection Engineering*. Quincy, Mass.: National Fire Protection Association.

NFPA. See National Fire Protection Association.

Nishi, J., F. Kamo, and K. Ozawa. 1990. Rational use of urban underground space for surface and subsurface activities in Japan. *Tunnelling and Underground Space Technology* 5 (1-2): 23-31. Pergamon Press.

Nuttall, N. 1988. Science. *New Scientist* 28 (April): 39.

Ogata, Y., T. Isei, and M. Kuriyagawa. 1990. Safety measures for underground space utilization. *Tunnelling and Underground Space Technology* 5 (3): 245-56. Pergamon Press.

Olds, A.R. 1985. *Nature as healer. Readings in Psychosynthesis: Theory, Process, and Practice*, 97-110. Toronto: Ontario Institute for Studies in Education.

Olds, A.R., and P.A. Daniel. 1987. *Child Health Care Facilities.* Washington, D.C.: Association for the Care of Children's Health.

Orians, G. 1980. Habitat selection: general theory and applications to human behavior. *The Evolution of Human Social Behavior* 49-66. Chicago: Elsevier (as cited in Heerwagon 1990).

Passini, R.

—1984. *Wayfinding in Architecture.* New York: Van Nostrand Reinhold.

—1985. Sign systems, maps, and wayfinding. *Proc.Int. Conference on Building Use and Safety Technology.*

Pauls, J. 1988. Movement of people. *Fire Protection Engineering.* Quincy, Mass.: National Fire Protection Association.

Paulus, P.B. 1976. On the psychology of earth covered buildings. *Underground Space* 1 (2) : 127-30. Pergamon Press.

Pilon, P. 1980. In Paris, a "city center" goes underground. *Underground Space* 5 (2): 102-20. Pergamon Press.

Porter, T., and B. Mikellides. 1976. *Color for Architecture.* New York: Van Nostrand Reinhold.

Proulx, G., and J. Sime. 1991. To prevent panic in an underground emergency: Why not tell people the truth? *Fire Safety Science.* Proc. 3rd Int. Symp. on Fire Safety Science. London: Hemisphere Publishing Corporation.

Rappoport, A., and R.E. Kantor. 1967. Complexity and ambiguity in environmental design. *APA Journal* 33 (4): 210-21, American Inst. of Planners.

Rohles, F.H., and W. Wells. 1977. The role of environmental antecedents on subsequent thermal comfort. *ASHRAE Transactions* 83:21-29 (as cited in Wise and Wise 1984).

Rosenthal, N.E., et al.

—1984. Seasonal affective disorder: A description of the syndrome and preliminary findings with light therapy. *Archives of General Psychiatry* 41 (Jan.): 72-80.

—1985. Antidepressant effects of light in seasonal affective disorder. *American Journal of Psychiatry* 142 (2): 163-70.

Ruys, T. 1970. *Windowless Offices.* M.A. Thesis, Univ. of Washington (as cited in Collins 1975).

Savinar, J. 1975. The effect of ceiling height on personal space. *Man-Environment Systems* 5:321-24 (as cited in Wise 1985).

Sawada, H., and T. Hane. 1991. Comparison between Japanese and American word imagery used to describe underground space. A paper presented at the Symp. for Utilization of Underground Spaces.

Scuri, P., and D. Skene. 1990. Spaces without windows. *Coming of Age*. Proc., Environmental Design Research Association Annual Conf., EDRA 21, Univ. of Illinois at Urbana-Champaign.

SEMAH. 1979. *10 ans d'activités aux Halles*, (Société anonyme d'économie mixte d'aménagement, de rénovation et de restauration du secteur des Halles).

Sharon, I.M., R.P. Feller, and S.W. Burney. 1971. The effects of lights of different spectra on caries incidence in the golden hamster. *Archives of Oral Biology* 16 (2): 1427-31.

Sillam, M. 1989. "L'aménagement des Halles," *Hygiène et prévention dans les ouvrages en sous-sol*, CEGIBAT.

Sime, J. 1985. Movement toward the familiar. Person and place affiliation in a fire entrapment setting. *Environment and Behavior* 17 (6): 697-724. Sage Publications.

Sime, J., G. Proulx, and M. Kimura. 1990. *Evacuation Safety in the Sub-surface Stations of Tyne and Wear Metro: Case Study of Monument Station*. Stage 2 of a use safety evaluation on behalf of Tyne and Wear Passenger Transport Executive, Newcastle upon Tyne, U.K.

Smith, R.D. 1986. Light and health - A broad overview. *Lighting Design and Application*, Feb.

Smith, R., and R. Holden. 1980-91. Personal communications with Univ. of Minnesota building officials.

Sommer, R. 1974. *Tight Spaces: Hard Architecture and How to Humanize It*. Englewood Cliffs, N.J.: Prentice Hall.

Spivack, M., and J. Tamer. 1981. *Light and Color: A Designer's Guide*. Washington, D.C.: American Institute of Architects Service Corporation.

Sterling, R.L., and J. Carmody. 1990. The experience with innovative underground structures at the University of Minnesota. *Proc. Int. Symp. on Unique Underground Structures*, Denver, Colo., June 12-15, 1990, 1(77):1-19, ed. R.S. Sinha. Golden, Colo.: CSM Press, Colorado School of Mines.

Sterling, R., J. Carmody, and W. Rockenstein. 1988. Development of life safety standards for large mined underground space facilities in Minneapolis, Minnesota, USA. *Proc. Third Int. Conf. on Underground Space and Earth Sheltered Buildings*, Shanghai, PRC.

Su, Y., and F. Peng. 1990. Psychological effect of underground space environment to human beings and the design countermeasures. *Tunnel and Underground Works Today and Future*. Proc. Int. Congress, International Tunnelling Association Annual Meeting, Cheng Du, PRC.

Tiedje, B. 1987. *Spaciousness - The Illusion and the Reality*. M.A. Thesis, Univ. of Washington.

Tilley, R.D. 1990. 3M Austin Center. *Architecture*, Aug.: 90-91.

Titus, W.C., M. Dainoff, M. Hill, R. Oskamp, B. McClelland, and R. Riley. 1977. The psychophysics of mass-space. *Man-Environment Systems* 6:370-71 (as cited in Wise and Wise 1984).

Tong, L. 1990. Fire - the harmful disaster for underground space use. *Tunnel and Underground Works Today and Future*. Proc. Int. Congress, International Tunnelling Association Annual Meeting, Cheng Du, PRC.

Ulrich, R.

—1979. Visual landscapes and psychological well-being. *Landscape Research* 4 (1): 17-23.

—1981. Natural versus urban scenes: Some psychophysiological effects. *Environment and Behavior* 13:523-56.

—1983. Aesthetic and affective response to natural environment. *Behavior and the Natural Environment*, eds. I. Altman and J.F. Wohlwill. New York: Plenum Press.

—1984. View from the window may influence recovery from surgery. *Science* 224:420-21.

—1986. Human responses to vegetation and landscapes. *Landscape and Urban Planning* 13:29-44.

Wada, Y., and H. Sakugawa. 1990. Psychological effects of working underground. *Tunnelling and Underground Space Technology* 5 (1-2): 33-37. Pergamon Press.

Watson, N., and I. Payne. 1968. The influence of fluorescent lamps of different color on the perception of interior volume. Environmental Research Group, Univ. of London (as cited in Kuller 1981).

Webber, G., and P. Hallman. 1988. Movement under various escape route lighting conditions. *Safety in the Built Environment*, ed. J.D. Sime. London: E. and F.N. Spon.

Wells, B. 1965. Subjective responses to the lighting installation in a modern office building and their design implications. *Building Science* 1:57-68 (as cited in Collins 1975).

West, M.J. 1986. *Landscape Views and Stress Response in the Prison Environment*. M.A. Thesis, Univ. of Washington.

Whitehead, L.A., B. Lee, J. Scott, and B. York. 1986. A demonstration of large scale core daylighting by means of a light pipe. *1986 International Daylighting Conference II*. Long Beach, Calif.

Williams, R. 1990. *Notes on the Underground*. Cambridge, Mass.: MIT Press.

Wilson, L.M. 1972. The effects of outside deprivation on a windowless intensive care unit. *Archives of Internal Medicine* 130:225-26.

Wise, B.K., and J.A. Wise. 1987. *The Human Factors of Color in Environmental Design: A Critical Review*. Dept. of Psychology, Univ. of Washington. A report to NASA.

Wise, J.A.
—1985. *The Qualitative Modelling of Human Spatial Habitability*. College of Architecture and Urban Planning, Univ. of Washington. A report to NASA.
—1986. A qualitative model of human spatial habitability. *30th Annual Meetings of the Human Factors Society*. Dayton, Ohio.

Wise, J.A., and E. Rosenberg. 1988. The effects of interior treatments on performance stress in three types of mental tasks. Grand Valley State Univ., Mich. CIFR Technical Report No.: 002-02-1988.

Wise, J.A., and B.K. Wise.
—1984. Humanizing the underground workplace: Environmental problems and design solutions. *First International Symposium on Human Factors in Organizational Design and Management*, eds. O. Brown and H.O. Hendricks. North-Holland: Elsevier Science Publishers BV.
—1988. (eds.) *The Human Factors of Underground Work Environments*. Center for Integrated Facilities Research, Grand Valley State Univ., Mich.

Wohlwill, J.F. 1983. The concept of nature: A psychologist's view. *Behavior and the Natural Environment*, eds. I. Altman and J.F. Wohlwill. New York: Plenum Press.

Wools, R., and D. Canter. 1970. The effect of the meaning of buildings on behavior. *Applied Ergonomics* 1 (3): 144-50 (as cited in Wise 1985).

Wotton, E. 1981. *Windows and Well-being in the Workplace.* Prepared for Health and Welfare Canada, Health Facilities Design, Ottawa, Ontario.

Wurtman, R.

—1968. Biological implications of artificial illumination. *Illuminating Engineer*, Oct.: 523-29.

—1969. The pineal and endocrine function. *Hospital Practice* 4 (Jan.): 32-37.

—1973. Biological considerations in the lighting environment. *Progressive Architecture* 9:79-81 (as cited in Levin and Duhl 1984).

Wurtman, R., M. Baum, and J. Potts (eds.). 1985. *The Medical and Biological Effects of Light.* Annals of the New York Academy of Sciences, 453.

Wyon, D.P., and I. Nilsson. 1980. Human experience of windowless environments in factories, offices, shops, and colleges in Sweden. *Proceedings of the Eighth CIB Triennial Congress*, Oslo, Norway.

Ylinen, J. 1989. Architectural design, spatial planning. *The Rock Engineering Alternative*, ed. K. Saari. Helsinki: Finnish Tunnelling Association.

Zamkova, M.A., and E.I. Krivitskaya. 1966. Effect of irradiation by ultraviolet erythema lamps on the working ability of school children. *Gig. i Sanit.* 3:41-44.