Minimizing Land Used by Automobiles and Buses in Urban Central Core: Underground Highways and Parking Facilities

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Possibilities for reducing the land used for urban transportation in the central city core by providing ample automotive access with deep underground tunnels and parking areas are examined.

The cost of conventional urban highways built through densely populated areas is described in terms of construction costs, right-of-way acquisition costs, and selected operating expenditures. Construction and ventilating costs of vehicular tunnels are presented to permit a comparison with highway costs. The data imply that if existing trends continue, it might be cheaper before the end of this century to move and park passenger cars and buses under ground rather than above ground in the center of many American cities.

Some design features of underground construction and travel are also considered, such as tunneling machines, rock removal, prefabricated lining and roadways, adaptability to mass transit systems, land reclamation, traffic control, and obstacle removal.

The study considers what may be needed if all mass transit ridership were hypothetically transferred to passenger cars in Los Angeles, Chicago, and Manhattan. Recommendations are given for study of the underground highway concept and developments of prototype machines capable of rapid excavation of vehicular tunnels under most rock conditions.

•THE AMERICAN metropolis is steadily expanding, and its inhabitants, as their incomes grow, are acquiring more and more automobiles. Moreover, these trends are occurring not only in American cities but throughout the world. The passenger car is the most surface-consuming transportation vehicle in wide use today and, as a result, access to the central core of the city by individual transportation should be a prime concern to city planners.

If we expect to preserve the central city as we know it today and handle the large traffic volumes required in major cities, innovations in current practices are required. The minimization of land used in conducting automotive and bus traffic on the surface of city streets is the first step, and the possibility of eliminating surface usage for transportation by removing auto and bus traffic from the surface and relegating it to either aboveground or underground facilities is the primary concern of this study. With the choice between elevated highways and high-rise parking structures, and deep underground roads and storage garages, for economic and aesthetic reasons the underground concept was chosen here to be studied, although aboveground facilities should also receive attention.

The purpose of this report is to investigate and suggest further study of underground vehicular travel (i.e., multilane deep subterranean highways and ample parking facilities with outlets to the surface only in the suburbs) as one alleviation of the central

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city's traffic and land-use problems. This vast urban land conservation program involves consideration of some staggering expenditures, but there are benefits that can be reaped in numerous other areas where we now pay dearly for the highway and road designer's practice of using mostly the surface of the city for car, truck and bus traffic.

To be sure, near the hubs of some American cities, vehicular tunnels (such as those leading into Manhattan) or subterranean parking facilities (as in Boston, San Francisco, Los Angeles, and New York) already exist or are being planned (such as the Beverly Hills freeway), but in no instance are the tunnels connected directly to the parking facilities or do the parking areas tend to decongest surface traffic (but rather the opposite); in most situations they account only for a very minute portion of the vehicular volume.

Naturally the city planner cannot consider only subterranean highways without also considering connected subsurface parking garages. If only ample parking were provided, the surface traffic congestion would deny access to such facilities; likewise, with ample underground traffic density but no place to stop and park underneath the destination, the purpose of the tunnels would also be defeated. Thus, no inlet or outlet to the surface, except for passenger and freight elevators, should exist to congest city streets.

The conjunction of the two schemes—road and parking—is essential at all stages of the design: at the conceptual stage (since tunneling machines must be developed as a very first step for both deep underground parking garages and highway tubes), at the engineering stage (where large commitments and expenditures are defined and funds must be procured), at the construction stage (where the huge amounts of excavated material must be disposed of efficiently), and certainly at the initial use stage.

The plan of this study is to plot over a half-century span the cost of constructing and operating selected conventional urban highways and their right-of-way cost. The costs of some automobile vehicular tunnels built in this century are presented for comparison. In the not-too-distant future these costs are observed to merge, giving some economic basis to the underground concept. The operating costs of highways and tunnels are also listed and compared, and those for underground roads are shown to be lower already than those for equal-capacity surface roads in many instances. Since underground urban automotive traffic might not involve much greater costs than surface traffic in the future, the design features and advantages of future urban highways and parking are investigated. It is recommended that a three-lane tunneling borer be developed as a first approach.

COST OF URBAN SURFACE HIGHWAYS

The initial construction cost of selected major roads and highways is shown in Tables 1 and 2, where the entries were arranged neither by date nor by magnitude. The costs are those of the construction contract at the time it was awarded or of the planning estimate, and are distinguished where possible from the cost of acquisition of the right-of-way. Demolition costs are either in land or in construction costs, since they are accounted for differently in various localities; they tend to be the least of the three major ingredients of urban highway prices, varying from negligible amounts in the West to sizable amounts in the East.

The entries in Tables 1 and 2 encompass a wide spectrum of freeways, differing greatly in environment, materials, design criteria, and time of completion. For example, the spectrum extends from the surface highways built in the first third of this century to the grade-separated contemporary freeways, either depressed or elevated, and from the multiple-access 40- to 50-mph roads to the limited-access 80-mph freeways with cloverleaf interchanges. Materials and methods encountered vary from excavation in hard rock to removal of loose soil, and from concrete paving practices to the use of bituminous aggregate. Finally, although some of the highways are austere, essentials only, arrangements common before World War II, others tend to have elaborate bridge crossings and divided medians with landscaping, requiring expensive detouring roads during construction.

TABLE 1

DATA ON SOME HIGHWAYS

	Name and Location[a]	Lanes	Length (miles)	Completion Date	Cost (millions of $) Construction	Cost (millions of $) Lane-Mile	Type of Area[b]	ENR Reference Date	ENR Reference Page	Remarks
o	Capital Beltway, Md., Va., Wash. D.C.	6/8	65	1965	200	0.44	S-R	1/25/62	93	.....
1.	Boston Inner Belt	6	25	1965	180	2-3	UHD	1/25/62	88	Cost multiplied by 2 for contingencies
o	Hartford - Norwich, Conn.	6	74	1961	61	0.14	S	1/25/62	88	.....
o	Palmetto, Miami Bypass, Fla.	4	25	1961	30	0.30	S	1/25/62	88	.....
o	Ohio No. 71	4	44	1962	25	0.14	R	1/25/62	95	.....
o	Danbury-Newton, Conn.	4	24	1962	35.5	0.37	S-R	1/28/62	141	.....
o	New Jersey Expressway	6	32	1962	65	0.34	S-R	1/28/62	142	.....
2.	Crossbronxway, N.Y.	6	5.4	1962	120	3.7	UHD-LD	1/28/62	142	Extension
5.	Embarcadero, San Francisco, Calif.	8	2.6	1960	15.6	1.0	---	1/28/62	49	Right of way acquired at almost no cost on existing roadways
o	Connecticut Turnpike	4/6	129	1959	445	0.69	UHD-S-R	2/19/59	78	.....
6.	Crossbronxway, Phase 1, N.Y.	6	2.3	1958	32.1	2.3	UHD	2/19/59	78	.....
7.	Edsel Ford, Detroit, Mich.	6/8	14	1959	44	0.45	S	2/19/59	86	Not plotted
8.	Chrysler Expressway, Detroit, Mich.	6/8	3.4	1960's	69	2.9	UHD	2/19/59	86	.....
9.	Spokane Freeway, Wash.	6	2.1	1958	11	0.89	UHD-LD	2/19/59	88	.....
10	San Francisco Central, Calif.	8	1.4	1958	7.8	0.7	---	2/19/59	42	Double-decking cut land acquisition costs in half
11.	Central Artery, Boston, Mass.	4/6	4.1	1951-58	100	4.9	UHD	2/13/58	168	2nd portion may include right-of-way cost: plotted only $3.5/lane-mile
12.	Congress Street, Chicago, Ill.	8	9	1957	106	1.5	UHD	2/13/58	180	Has rail line down median divider
13.	Lodge Expressway, Detroit, Mich.	6/8	9.4	1958	90	1.4	UHD	2/13/58	184	.....
o	Portion of Santa Ana Freeway, Calif.	6	42.9	1958	76.5	0.3	S	2/13/58	194	.....
o	Portion of San Bernardino Freeway, Calif.	6	30.7	1958	54	0.29	S	2/13/58	194	.....
14.	Lunalilo Freeway, Honolulu, Hawaii	8	7.5	1965	55	1.2+?	ULD	4/19/62	25	Cost multiplied by 1.3 for contingencies
15.	Hudson Tunnel Approaches, N. J.	4	0.8	1927	1.75	0.55	ULD	4/30/25	733	.....
16.	New Jersey Meadows, Passaic-Hackensack	4	3.0	1933	18	1.5	ULD	6/12/30	973	.....
17.	Ogden Ave. Diagonal Expressway, Chicago, Ill.	6	2.8	1932	12	0.75	ULD	12/17/31	952	.....
18.	Westside Expressway, Canal to 72nd St., N.Y.	6	6.7	1937	24.3	0.6	UHD	10/14/37	616	.....
19.	Proposed Chicago Elevated Road	4	7	1933	18	0.64	ULD	4/27/33	536	Proposed but never built due to Depression
o	Proposed Chicago Surface Road	4	7	1933	20	0.72	ULD	4/27/33	536	.....
o	Sepulveda Pass, San Diego Freeway, Calif.	8	5.7	1962	20	0.44	R	(c)		Portion over Santa Monica mountains
o	Merritt Parkway, Conn.	4/6	45	1938	13	0.06	S	4/27/33	536	Land acquisition costs were 1/2 of construction
20.	Arroyo Seco, Los Angeles - Pasadena, Calif.	4+	6.2	1940	5.2	0.21	ULD	8/15/40	203	Right of way cost 1/2 of construction
21.	Brooklyn Belt Parkway, N.Y.	4/6	33	1940	70	0.42	ULD	7/11/40	60	Estimated cost of 1946 construction: $30 million
22.	East Boston Expressway, Mass.	4	1.9	1951	12	1.6	ULD	3/17/44	121	.....
23.	Major Deegan, Triboro Bridge - City Limits, N.Y.	6	7.5	1956	63.6	1.4	ULD	2/16/56	149	.....
24.	Boston Central Artery, Mass.	4/6	2.8	1953	14.8	1.1	ULD	2/14/52	109	1st phase
o	New Jersey Turnpike	6	118	1951	255	0.36	R	2/14/52	110	.....
o	Penn-Lincoln Parkway West, Pa.	4	9.2	1953	14	0.38	S	2/14/52	110	.....
25.	Embarcadero, San Francisco, Calif.	8	3.9	1954	13.7	0.45	ULD	2/16/56	163	1st portion; free right of way; elevated
26.	Hollywood Freeway, Hollywood, Calif.	6	8.1	1955	27	0.6	ULD	2/16/56	---	.....
28.	Harlem River Drive, N.Y.	4/6	2.5	1956	20.4	1.63	UHD	2/16/56	149	.....
30.	Calumet Skyway, Chicago, Ill.	8	8	1958	106	1.65	UHD	2/16/56	149	.....

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[a] Numbers relate to data points on Figs. 1, 2, and 3.

[b] S = Suburban; R = Rural; UHD = Urban, High Density; ULD = Urban, Low Density.

[c] Data from Los Angeles Times, December 1962.

TABLE 2

DATA ON SOME HIGHWAYS (INCLUDING RIGHT-OF-WAY COSTS)

(Numbers in brackets indicate estimated breakdown of total project costs)

	Name and Location[a]	Lanes	Length (miles	Completion Date[b]	Construction Cost Estimate (millions of $) Total	Construction Cost Estimate (millions of $) Lane-Mile	Right-of-Way Cost Estimate (millions of $) Total	Right-of-Way Cost Estimate (millions of $) Lane-Mile	Type of Area[c]	Remarks
31.	Glendale Freeway, Glendale, Calif.	8	2.7	1963	12	0.56	15.5	0.72	ULD	.....
32.	Harbor Freeway, Los Angeles - San Pedro, Calif.	8	--	1954	--	--	--	0.5	ULD	.....
33.	Golden State Freeway, Boyle Heights, Los Angeles, Calif.	8	--	1952	--	--	--	0.38	ULD	Los Angeles Times, Part II, 1/28/63, p. 1
34.	Golden State Freeway, Riverside Dr., Los Angeles, Calif.	8	--	1953	--	--	--	0.46	ULD	.....
35.	Urban portion of Interstate System	5.7	4,200	1961	10,000	0.41	3,600	0.15	ULD-S	House Document No. 54, 87th Cong., 1st Sess.; total re-estimate, 1961: not plotted; very few roads penetrated CBD
36.	Santa Monica Freeway, Los Angeles, Calif.	8	17.1	1965	--	--	98.5	0.72	ULD	Los Angeles Times, 2/9/63
37.	M-1 Motorway, London - Birmingham, England	4	10	1964	32.2	0.8	--	--	ULD	New York Times, 2/12/63; northern London suburbs
38.	Pasadena (East-West) Freeway, California	8	5.9	1966	23	0.5	38	0.8	ULD	California Division of Highways estimates (plotted x 1.5 for contingencies)
39.	Lower Manhattan Crosstown Expressway, N. Y.	6	2.5	1959	47	2.5-3.5	31	1.5-2.5	UHD	New York Port Authority estimates; project abandoned
40.	Mid-Manhattan Crosstown Expressway, N. Y.	6	2.0	1959	38	3.2	33	2.7	UHD	New York Port Authority estimates; project held in abeyance
41.	Prospect Expressway, Gowanus - Prospect, N. Y.	6	2.1	1961	20	1.6	8.6	0.7	UHD	New York Port Authority estimates
42.	Marine Freeway, Culver City, Calif.	8	3.2	1963	15	0.59	--	--	S	Los Angeles Times, 2/24/63 (plotted x 1.2 for contingencies)
43.	Congress Expressway, Chicago, Ill.	8+	16.5	1960	133	0.95	55	0.39	UHD	.....
44.	Northwest and Edens, Chicago, Ill.	8-12[d]	15.6	1961	173	1.2	70	0.5	UHD	Literature from Historical Section, Expressway Office, City of Chicago
45.	South (Ryan) Expressway, Chicago, Ill.	8-14[e]	13	1963	114	0.88	66	0.51	--	.....
o	Foremost Freeways in Los Angeles, Calif.									Status as of January 1962
46.	Golden State	8	29.6	--	76	0.34	70	0.32	ULD	Not plotted; disagrees with entries 33 and 34
47.	Hollywood	8	11.6	1959	37	0.40	35.6	0.38	UHD	Not plotted; disagrees with entry 26
48.	San Diego	8	55.1	--	127.6	0.21	92.7	0.29	ULD-R	Not plotted; part through uninhabited land
49.	Santa Monica	8	4.8	--	46.8	2.1	82.3	1.2	UHD	.....
50.	Long Beach	8	19.7	1958	33	0.15	23.2	0.21	ULD	Not plotted; much of land cleared by early 1950's
51.	Harbor	8	22.2	1959	50.3	0.28	53	0.3	ULD	Not plotted; disagrees with entry 32
52.	Foothill	8	2.3	--	2.4	0.49	8.5	0.13	S	Right of way not plotted; mostly vacant land
53.	Glendale	8	2.4	1958	6.1	0.35	6.8	0.31	S	Plotted for time of expenditures (early 1950's)
54.	Ventura	8	37.3	--	61.4	0.15	44.5	0.21	S	Not plotted
55.	Colorado	8	2.3	--	6.3	0.34	2.5	0.13	S	Not plotted
56.	Downtown San Diego	8	1.6	1962	6.0	0.47	2.8	0.22	ULD	Los Angeles Times, 3/10/63, p. A; 4-level exchange
57.	Brooklyn - Queens Expressway, N. Y. (Total)	6	12.3	--	94	1.27	26.4	0.36	ULD	
58.	Battery-Brooklyn Tunnel to Brooklyn Bridge	6	1.8	1940/54	[35]	3.2	[10.7]	1.0	ULD	
59.	Brooklyn Bridge to Navy St.	6	1.2	1954/59	[7]	1	[3.4]	0.5	ULD	
60.	Navy to Steuben St.	6	1.1	1954/59	[12]	1.8	[4.8]	0.73	ULD	
61.	Bedford to Grand Ave.	6	0.5	1952/59	[4]	1.3	[1.8]	0.6	ULD	
o	Long Island Expressway, N. Y. (Total)	6	86	--	169	0.33	48	0.09	ULD	New York Port Authority estimates
62.	Queens-Midtown Tunnel to Brooklyn-Queens Expressway	6	--	1941	4.2	0.47	0.95	0.1	ULD	
63.	Brooklyn-Queens Expressway to Queens Blvd.	6	3.4	1941/50	[25]	1.23	[4]	0.2	ULD	
64.	Queens Blvd. to Grand Central Parkway	6	1.2	1954/58	[3.5]	0.5	[1.6]	0.2	ULD	Right of way not plotted
65.	Grand Central Parkway to 136th St.	6	0.8	1955/59	[4]	0.83	[2.6]	0.54	ULD	
66.	136th St. to Parsons Blvd.	6	1.1	1954/57	[3.5]	0.53	[1.6]	0.24	ULD	Right of way not plotted
67.	Parsons Blvd. to 190th St.	6	1.4	1956/59	[4]	0.48	[2.3]	0.27	ULD	Not plotted
68.	190th St. to Cloverdale Rd.	6	1.9	1958/60	[9.5]	0.83	[4]	0.35	ULD	Right of way not plotted
69.	Gowanus Expressway, Battery - Brooklyn, N. Y.	6/8	5.1	1961	65.3	2.0	18.4	0.56	ULD	
o	Narrows Bridge, N. Y.	12	1.5-2.5	1967	320[f]	13	--	--	--	

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[a] Numbers relate to data points on Figs. 1, 2, and 3.

[b] Estimated or actual.

[c] S = Suburban; R = Rural; UHD = Urban, High Density; ULD = Urban, Low Density.

[d] Nine-lane average.

[e] Ten-lane average; 2 miles elevated.

[f] Total construction and right-of-way cost estimate.

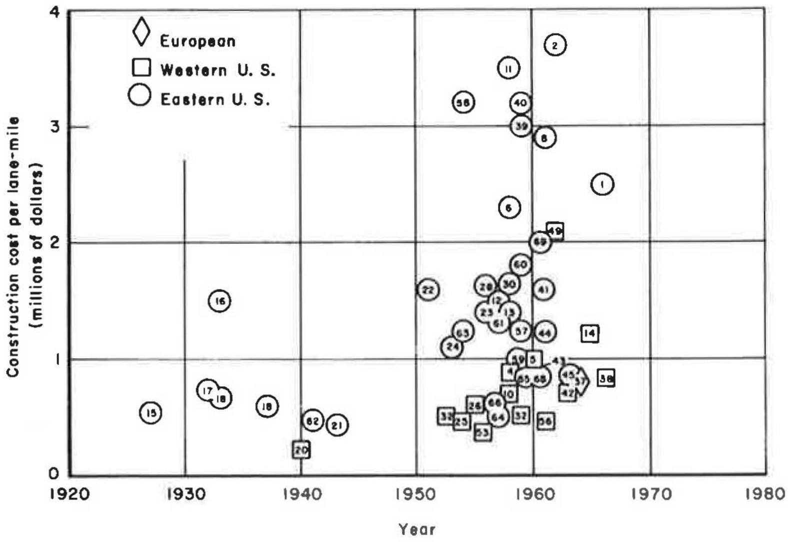


Figure 1. Construction cost of urban highways (numbers keyed to entries in Tables 1 and 2).

It is interesting to plot the data on urban highways and freeways of Tables 1 and 2 through the more densely populated areas—as was done in Figures 1 and 2—leaving out all narrow expressways and suburban and rural highways and roads. The plot of total project costs of urban highways (Fig. 3) appears to be scattered over a wide pattern; nevertheless, it shows a painfully well-known fact, that even the lowest costs of building an expressway through densely populated areas are inexorably rising with the passage of time.

Construction costs of urban highways have exceeded, both in rate of growth and in magnitude, all other analogous costs of general construction and building (Fig. 4) and seem to parallel the wages of construction equipment operators—wages that in the past decade have doubled in magnitude and increased linearly in time. This has come about through the steep rise in the demand for speed, safety, and comfort by the

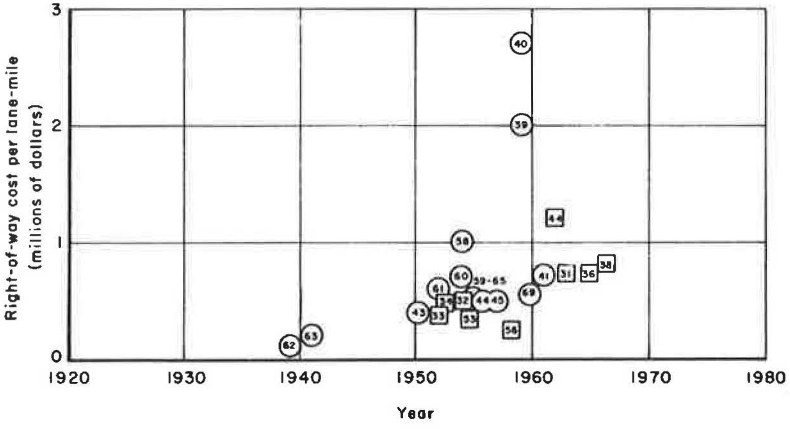


Figure 2. Land acquisition cost of urban highways (numbers keyed to entries in Tables 1 and 2).

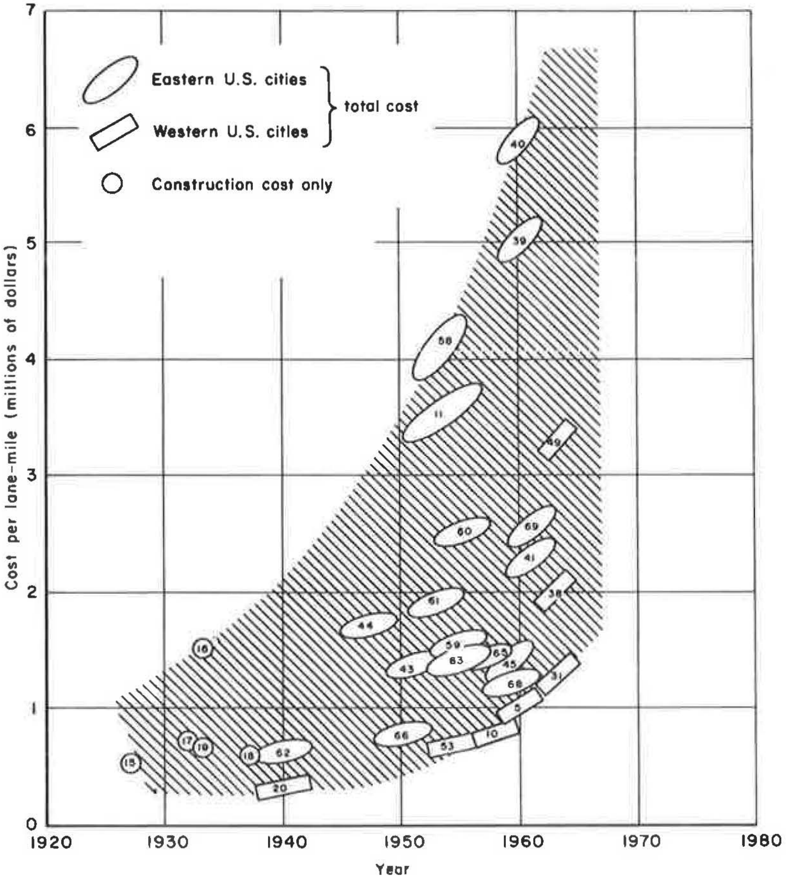


Figure 3. Total costs of some urban highways (numbers keyed to entries in Tables 1 and 2).

motoring public, which is reflected in a widening and upgrading of design specifications for freeways.

Adopting the lane-mile as the common denominator for initial costs of urban freeways is an oversimplification that neglects a large number of other local factors influencing the cost of demolition, land, and construction for surface highways:

1. Emergency parking shoulders—These may vary from no provisions at all (common in some eastern cities) to as much as 8 ft or more (required in some western localities).
2. Median-strip allowance—Again this may vary, even within a single locality, from a meager 2-ft curb with a bounce-back fence to as much as a 100-ft swath, complete with extant rail lines.
3. Slopes on cut or fill—In many instances this necessity of construction requires more than half of the right-of-way of the whole highway.
4. Number, frequency, and elaborateness of interchanges, on- and off-ramps, bridges, and other crossings—In the distant future, as intersecting freeways proliferate, interchange costs might well become a more important cost indicator than the total amount of lane-miles.
5. Unneeded increment in right-of-way—This is caused by the availability of lots and their dimensions in integral multiples.

Highways were classified by dollars per lane-mile because this criterion appeared convenient for vehicular tunnel costs also (as exemplified later by the tighter grouping

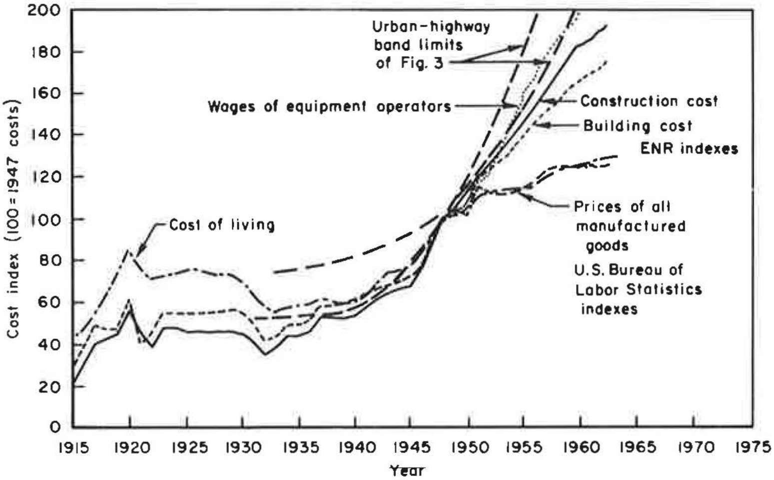


Figure 4. Comparison of some manufacturing and construction costs.

of tunnel cost data when plotted on this basis), and this was a common descriptor for the ultimate cost comparison of surface vs underground highways.

Urban highway costs could be predicted for a couple of decades in the future if desired, since the indicators (mostly vehicle design trends and consumer preferences) are foreseeable and steeply graded upward. For example, automobiles will be far more powerful, maneuverable and economical to operate than today's cars, and each of these sizably upgraded characteristics requires in turn a proportionately more expensive freeway design.

The continuing or running costs of operating urban highways may be divided into two groupings:

Group I—Policing and patrol, debris and wreck removal, pavement repair and painting, sign maintenance, emergency call system, traffic control and pacing, and miscellaneous; and

Group II—Snow and ice removal, fence and guardrail repair and upkeep, and maintenance and landscaping of medians, borders, and lighting.

The first group comprises expenditures common to both conventional on-the-surface and underground highways. Since these costs may be nearly equal for aboveground and subterranean urban expressways, they need not be evaluated in a comparison, even though they are quite significant in other contexts. The second group consists of some of the continuing operational costs of highways that may be avoided in driving cars under cities, rather than on their surface. The loss of tax revenue from property and land wiped out by a freeway has not been included in the continuing costs of highways, since it is seldom associated with expressway operation and might actually be redistributed to outlying areas in the form of derivatives from driver benefits.

Considering then only Group II expenditures, winter maintenance looms as a major item in non-California localities, and in Southern California landscaping maintenance costs constitute the major portion of operational costs. This portion of conventional maintenance costs has been lately between $500 and $2,000/lane-mi/yr and could be eliminated if freeways were to be operated underground (though other costs, such as for ventilation and lighting, to be discussed later, would arise that are not encountered on surface roads).

COST OF VEHICULAR TUNNELS AND UNDERGROUND HIGHWAYS

The initial capital project costs of some vehicular tunnels were compiled in Table 3. Projects outside the United States were included in this listing to show the disparity

TABLE 3

DATA ON SOME VEHICULAR TUNNELS

	Name and Location[a]	Lanes	Length (ft)	Completion Date	Cost (millions of $)		ENR Reference		Remarks
					Project	Lane-Mile	Date	Page	
1.	Allegheny No. 2, Pa.	2	6,070	1964	8.2	3.5	9/20/62	107	Competent rock; excavation, $\$10/\text{yd}^3$; complete job, $\$60/\text{yd}^3$
2.	Norfolk - Portsmouth, Va.	4	4,200	1962	22	6.9	1/25/62	94	Soft rock under river
3.	Sasago Mountain, Tokyo - Kofu, Japan	2	9,750	1959	3.6	0.97	3/19/59	130	High mountain rock; lowest labor costs (1/8 of U.S.)
4.	Fort Lauderdale, Fla.	4	864	1959	6.5	10	2/19/59	88	Under river; not plotted; data unreliable
5.	2nd Lincoln Tube, Midtown N. Y.	2	6,000	1940	29	12.7	8/26/37	330	Shield-driven; see 22 for 1st tube
6.	Harvey, New Orleans, La.	4	1,080	1957	4.5	5.5	2/13/58	161	.....
7.	Sumner Tunnel, Boston, Mass.	2	5,440	1934	25	12.2	4/24/30	702	Competent rock
8.	Callahan Tunnel, Boston, Mass.	2	5,500	1960	29	14	1/25/62	94	Cost assumed 40% lower than price; plotted as $10,000,000
9.	Patapsco River, Baltimore, Md.	4	7,650	1957	130	22	2/13/58	161	Much trench and fill; not a "driven" tunnel; not plotted
10.	Fort Pitt, Pittsburgh, Pa.	4	3,430	1957	10	3.8	2/13/58	174	.....
11.	Mt. Washington, Pittsburgh, Pa.	4	5,000	1957	17	4.5	2/13/58	174	.....
12.	Mont Blanc, Italy - France	2	38,050	1963	40	2.7	5/31/62	56	Unstable protogine; low labor cost (1/2 of U.S.)
13.	Kanmon, Honshu - Kyushu, Japan	3[b]	11,420	1958	22	4.1	(c)	--	150 ft below sea level; assuming 2-1/2 lanes
14.	IJsselmeer, Amsterdam	4	8,200	1967	39.5	6.3	4/19/62	47	Below sea level; prefab caissons
15.	Coentunnel, Amsterdam	4	4,710	1966	17.5	3.7	5/19/62	47	Below sea level
16.	Grand St. Bernard, Italy - Switzerland	2	19,000	1962	16	2.2	5/12/62	23	Highest tunnel; low labor cost (1/2 of U.S.)
17.	Viaduct under Dallas-Fort Worth Airport	6	813	1963	1.4	1.5	5/5/62	--	Cut and fill; trench and fill; not plotted
18.	Holland Tunnel, N. Y. - N. J.	4	3,100	1927	48	20	6/3/20 5/24/30	1127 697	Sunken sections; first under water in U.S.
19.	Liberty, Pittsburgh, Pa.	4	5,890	1930	30	6.7	5/7/25	764	Semicompetent geology
20.	Narrows, Brooklyn - Staten Island, N. Y.	4	10,400	1930	34	4.3	22/12/25	280	Proposed date; cost could be as high as $6,000,000
21.	Mersey River, Liverpool, England	3	11,300	1935	30	4.7	11/16/33	58	Under river
22.	1st Lincoln Tube, Midtown N. Y.	2	6,000	1937	37	16.3	3/1/34	304	Under Hudson River; see 5 for 2nd tube
23.	Transmanhattan (under 37th St.), N. Y.	6	7,000	1930	50[d]	6.3	9/9/37	444	Proposed date; tunnel never built
24.	Queens, Midtown, N. Y.	4	5,000	1941	21.3	5.6	7/8/37	42	Under East River
25.	Brooklyn-Battery, N. Y.	4	9,200	1951	82	11.5	3/17/49	123	.....
26.	Broadway Tunnel, San Francisco, Calif.	4[e]	1,620	1953	5.2	4.2	3/17/49	127	Competent rock; San Andreas and Hayward Faults
27.	3rd Bore, Broadway Tunnel, Alameda - Contra Costa, Calif.	2	3,300	1964	10	8	(f)	--	Incompetent geology
28.	Hazelview Summit, Crescent City, Calif.	2	1,890	1962	4	5.6	(g)	--	Competent rock
29.	San Bernardino, Italy - Switzerland	2	21,000	1964[d]	9-15	1.1 - 1.9	3/26/59	34	Competent rock; not plotted; plans only so far
30.	Splugen, Milano - Zurich, Italy - Switzerland	2	30,000	--	18[d]	1.6	3/26/59	34	Competent rock; not plotted; plans only so far
31.	London Transport System, Finsbury Park Segment, England	2	5,300	1961	2.8	1.4	(h)	--	Clay and mud; a drilled subway; not plotted

[a] Numbers relate to data points on Fig. 5.
[b] Two car lanes and one bicycle lane.
[c] Data from the Consulate.
[d] Estimated.
[e] Two bores with two lanes each.
[f] Data from California Highways and Public Works, July - August, 1960.
[g] Data from California Highways and Public Works, May - June, 1961.
[h] Data from City and Suburban News, Issue 36.

in costs between tunnels in the United States and others (due primarily to labor wage differentials). The costs here include the complete turn-key project (excavation, lining, pavements, lighting, ventilation equipment, turnarounds, etc.).

As with highways, the plot of the data from Table 3 (Fig. 5) exhibits a sizable scatter in the costs of tunnels, and only hints that the trend, in general, might be downward for American projects and uncertain for other countries. But, as before, there seem to be definable, though broad, bounds on vehicular tunnel costs in the United States, the lower of which tends to be some $2 million/lane-mi higher than costs outside this country. The upper bound generally represents shield-driven or sunken-type tunnel construction, and the lower bound represents driven tunnels.

The rate of decrease and the relative magnitude of vehicular tunneling costs can be explained in terms of ever-increasing mechanization of excavation and haulage, steady improvement in anticipating geological problems, and increased productivity in the country. That the costs seem to have bottomed is also explainable by dissecting the components of tunnel project cost. A comparison of entries 3, 12, 13, 15, 16, 29, 30, and 31 with American tunnels in Table 3 indicates that wages still constitute one-half of the capital tunneling cost in Europe and three-fourths of the United States tunneling costs. In other words, there is much to be gained by increasing the mechanization of tunnel boring, as recommended later. In addition, there is evidence that the cost of nonvehicular tunnels seems to be made up of two-thirds for excavation and one-third for lining, whereas for vehicular tunnels, the proportions might be one-half for excavation, one-fourth for lining (if lining is required), and one-fourth for roadbed and utilities.

The continuing or operating costs of vehicular tunnels may be divided into two groupings as was done for surface highways; the first comprises expenditures that are met on surface highways as well and the second comprises expenditures unique to vehicular tunnels:

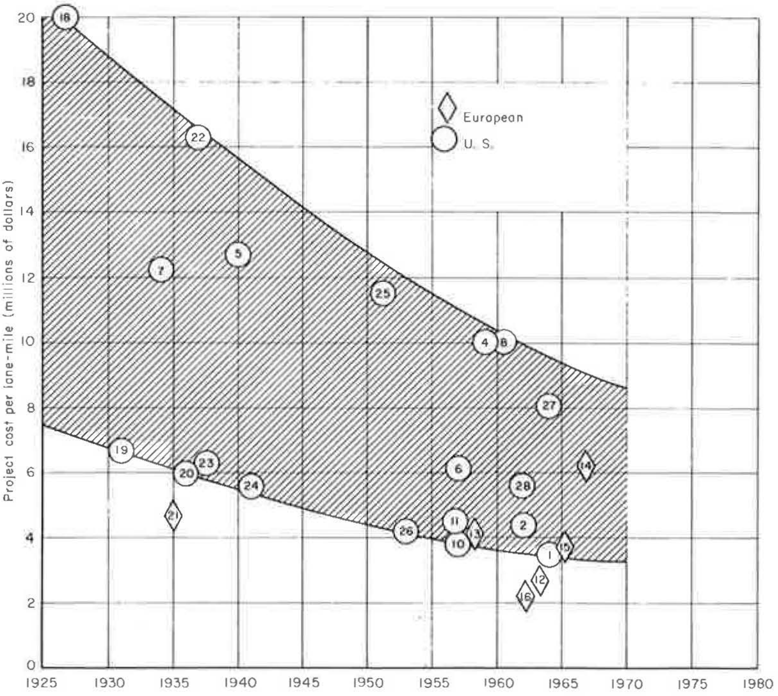


Figure 5. Cost of vehicular tunnels (numbers keyed to entries in Table 3).

Group I—Policing and patrol, nighttime lighting, debris and wreck removal, pavement and lining repair and maintenance, sign maintenance, emergency call system, traffic control and pacing, and miscellaneous; and
Group II—Daytime lighting, and ventilation.

As was done earlier for highways, only Group II costs need to be evaluated in this comparison between surface and subsurface highways, since comparable Group I costs are being incurred in surface highway operation. Lighting costs amount to a small fraction (1/20 to 1/10) of ventilation costs, leaving only ventilation costs as the major operational expenditure to be evaluated vis-a-vis the Group II costs of surface highways.

The ventilation provisions for long vehicular tunnels average at present about 80 to 90 cu ft of air per vehicle-mile, though in most cases this fresh air supply is grossly inadequate. Probably 150 cu ft/veh-mi would be a more satisfactory supply in the future; this corresponds to a ventilation power expenditure of about 6 w-hr/veh-mi. Assuming a tunnel traffic utilization of 5×10^6 veh/lane/yr (the recent integrated average for Manhattan access automobile tunnels) and an electricity cost of \$0.015/kw-hr, the power costs for ventilating a modern tunnel would be $(6 \text{ w-hr/veh-mi}) \times (5 \times 10^6 \text{ veh/lane-yr}) \times (\$0.015/\text{kw-hr}) \times (10^{-3} \text{ kw/w}) \times 10^{-2} = \$450/\text{lane-mi-yr}$. The total ventilating costs, including personnel, blower maintenance, and replacement, are double to quadruple the power costs alone and, thus, probably amount to some \$1,000 to \$2,000/lane-mi-yr by good and ample ventilation standards. These numbers are comparable to the Group II maintenance costs for surface highways.

Having observed that the operating costs of underground and surface highways are comparable, it might be worthwhile to summarize and compare capital costs of automotive tunnels and freeways. Replotting the entries and the bands of Figures 3 and 5 as in Figure 6, one notices that (a) the bands tend at present to merge, (b) cost differences between tunnels and new urban surface roads may be indistinguishable before the end of this century, and (c) tunnel unit costs are presently still decreasing, whereas highway costs are increasing.

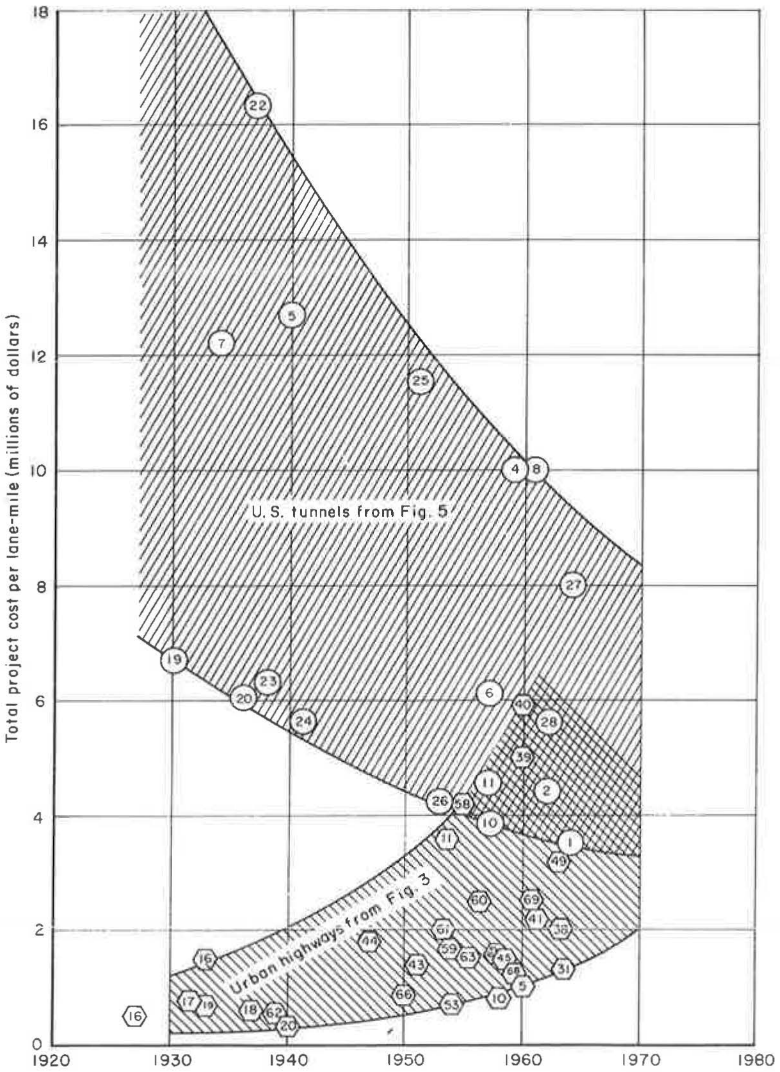


Figure 6. Cost of aboveground and underground highways in the United States.

The causes for these cost trends need careful investigation because they imply that automotive and bus travel and storage may soon be cheaper when conducted deep underground, below the central city. Our prediction is tempered only by factors that might seriously alter cost-curve slopes in the time period while underground systems are being considered. For example, it is clear that highway costs rise with increases in land values, demand for accessibility by car to urban areas, performance and convenience of passenger cars, wages of skilled operators of construction equipment, and general inflation.

Similarly, though tunnel construction cost is at present decreasing because of mechanization of tunnel driving and new boring technologies, this may only be a temporary situation, and in the future tunnel construction costs may also start going up for the very same reasons that highway costs are increasing today.

SOME DESIGN CONSIDERATIONS OF FUTURE URBAN-HIGHWAY TUNNELS

As an illustration of the features of future hypothetical underground urban highways and parking spaces, it might be interesting to imagine the construction of an eight-lane throughway, four lanes each way in each of two separate tubes or a more modest six-lane expressway of two tubes with three lanes each, as shown in Figure 7.

The assumption was that tunnels are machine drilled by a rotating mole rather than by the older manual labor-oriented procedure of pilot-hole drilling, blasting, benching, and muck removal. A 15-ft clearance is provided for the 12-ft wide lanes plus a 2-ft curb at the walls. These tunnels require prior development of counterrotating rock-boring machines, 21 to 27 ft in diameter, a technological feat that could be accomplished in the late 1960's, given enough research and funding impetus, and whose design is the main recommendation in this report.

The excavated cross-sections may vary from about 1, 200 sq ft for the four-lane tube to around 750 sq ft for the three-lane arrangement. Both cross-sections are less than the 1, 600 sq ft of a machine-driven outflow tunnel for the Mangla Dam in West Pakistan; the lower number is comparable to the 700 sq ft already driven in competent rock in the United States.

To excavate these tunnels in deep competent rock by present-day quasi-manual techniques might cost from $15/cu yd for, e. g., the Chicago subsurface to $20/cu yd for the Eastern littoral, whereas the finished tunnel (i. e., all debris removed and disposed of, tunnel roof lined, and roadways and utilities installed) could easily run to

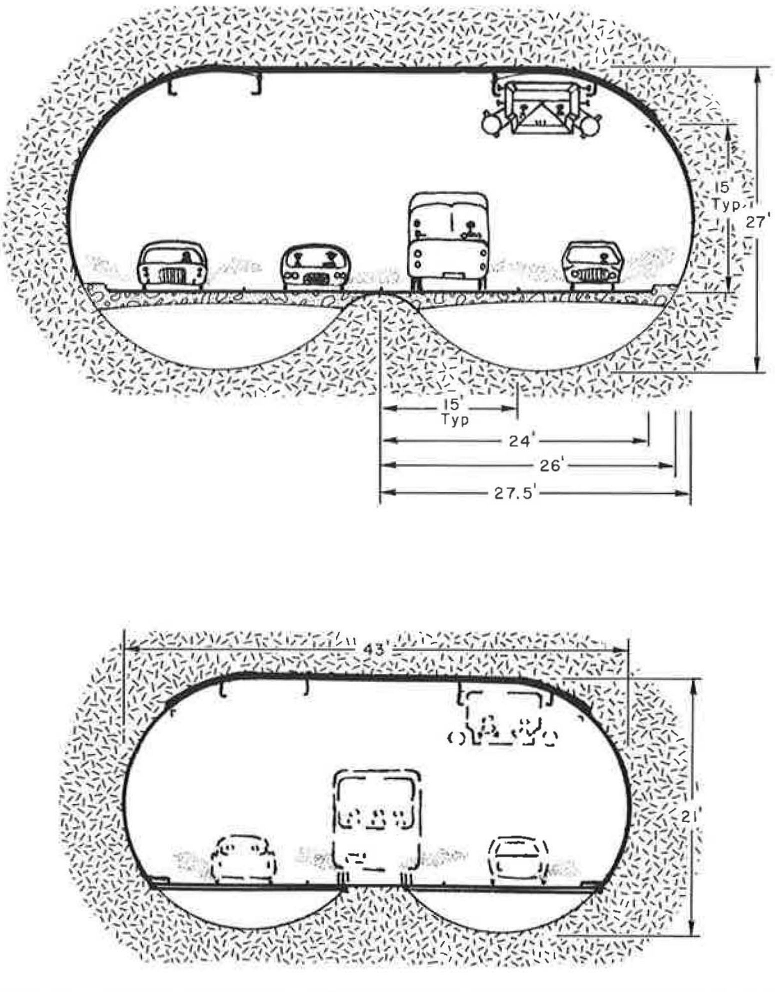


Figure 7. Layout of three- and four-lane machine-tunneled highways.

three times as much. So, in this decade, without machine boring, vehicular tunnels would cost about (\$15 to \$20/cu yd) × 3 × (250 to 300 sq ft/lane) × (5,280 ft/mi) /27 cu ft/cu yd or about $\$2.2 \times 10^6$ to $\$3.5 \times 10^6$/lane-mi—near the lower band limit in Figure 5. With a well-planned, long-range development program under the proper incentives and funding directed toward highly automated tunneling in hard rock, it would be logical to assume that the costs shown in Figure 5 could continue to drop in time, rather than to level off. The objectives of a tunneling machine research program aimed specifically at cost reduction (as recommended here) might encompass the design of:

1. Tunneling machines with counterrotating "bootstrap" drills (prototype example, Figure 8);
2. Continuous belts for conveying broken rock (muck) to prepared sites;
3. Lining and/or roof reinforcements for large-size bores that can be continuously emplaced by moving rigs closely following the drill; and
4. Prefabricated and standardized roadway slabs, fed continuously in long sections to a progressing machine that locates, levels, aligns, and firms them into place.

Though tunneling machines cannot at present bore vehicular tunnels in hard rock, they have a potential of halving excavation costs and could drive vehicular tunnels at satisfactory speeds, possibly as high as 1 mi/mo.

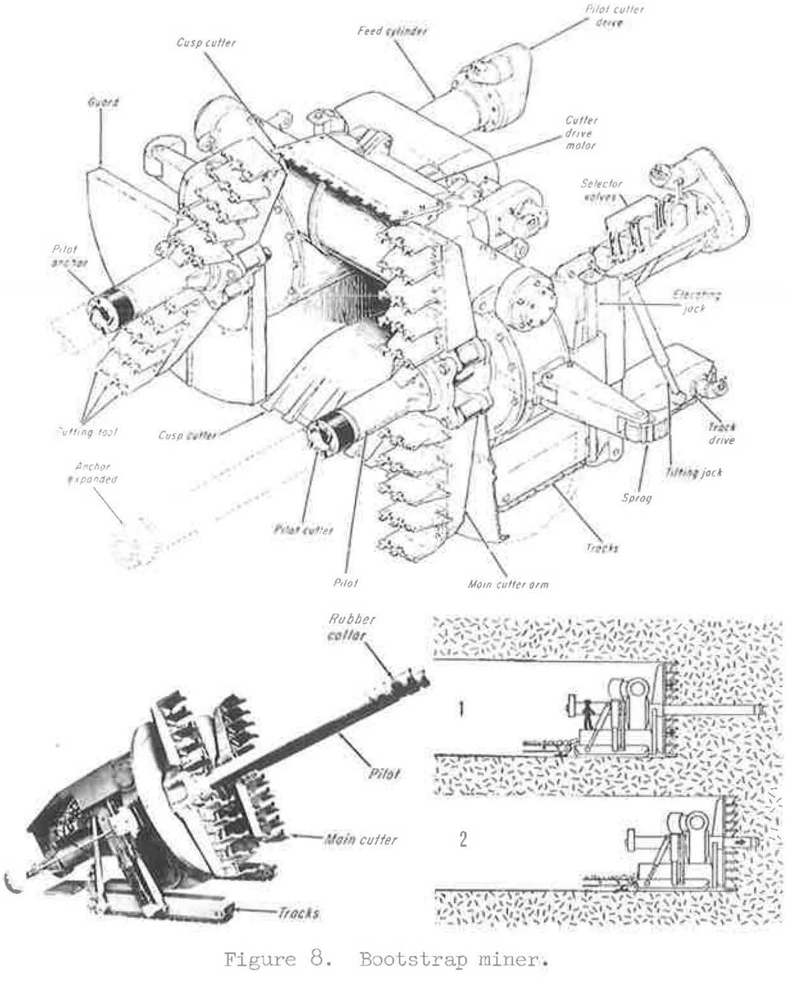


Figure 8. Bootstrap miner.

These recommendations for designing vehicular tunneling machines may be compared with present-day capabilities of single-hole boring machines ("moles"). The larger of these machines provide these advantages:

1. Safety beyond the drill-blast method—The smooth, round, and unshattered opening is inherently stronger than the equivalent blasted hole, and rockfall and lining requirements are greatly reduced. Also cutting, rather than blasting, minimizes the damage and faulting on the roof and sides of the hole and avoids damage and tremor inconvenience to surface property above the tunnel.
2. Precise excavation—In a concrete-lined tunnel, large amounts of concrete can be saved that would otherwise have to be used to fill the highly irregular and jagged voids beyond the required dimensions.
3. Low labor costs with the smaller crew needed—These have resulted in excavation costs as low as \$10 to \$12/cu yd in shale.
4. Rapid tunnel advance—Cutting rates as high as 150 ft/day have been recorded, and operating times as high as 50 percent have also been achieved in sedimentary rocks.
5. Better muck removal—The uniformly broken rock from the borer improves haulage and permits belt conveyal.

It must be remembered that these characteristics have already been demonstrated by tunnel borers of rather modest specifications. For example, most borers made in the United States and the Soviet Union are less than 10 m in diameter, powered with less than 1,000 hp, capable of advancing less than 12 ft/hr in limestone, shale or sandstone, and cost less than $\$10^6$.

Besides the suggestion for designing, fabricating and testing an automated tunneler, liner and roadway installer hopefully to cut further the costs of urban underground highways and parking facilities, some thoughts are offered on making these complexes more pleasant, safe, efficient, convenient, and cheaper to operate than surface roads by exploiting the subterranean environment.

Adaptability to Mass Transit Systems

Since these tunnels duplicate the desired route of mass transit systems, one or two of the lanes can be used for bus operation, or if the demand develops, for convoys of interlocked buses, or even for rail mass transit. The downtown visitor could be given at least the choice of driving his car and paying for fuel and underground parking fees or of riding more cheaply but inconveniently in a collective-transport vehicle. Traffic experiments on each route could quickly and continuously determine the optimum mix of private and mass transit vehicles.

Construction Without Interruptions

Tunneling does not disrupt the established patterns of surface activities in congested areas. Bores and parking caverns placed well below the network of utilities (water mains, power lines, sewers, gas and telephone conduits, and building foundations) do not necessitate expensive road detours. Work in underground facilities progresses steadily in all seasons and is immune to the vagaries of weather.

Possibilities for Land Reclamation

The broken rock that is drilled out of the bores can reclaim much urban land in the form of causeways, swamp fills, new airports on fill, beach-stabilizing jetties, etc.

Traffic Control Through Television

Central traffic surveillance and control by closed-circuit TV should be easy in the closed loop of subterranean freeways and parking facilities, since observing cameras installed almost at will above and along each lane and parking area open many possibilities for economical and efficient operation. One can think of the automated billing and collection of toll fees and parking charges, the opening and closing of on- and off-ramps to the suburban surface and to the parking facilities, instruction to motorists as to safe speed, shifting of directional signals, and the instantaneous detection of accidents, vehicle breakdowns, and location of roadway debris.

Overhead Patrol Cars

Policing and patrol cars could be designed for high-speed travel in either direction, suspended from electrified rails in the tunnel ceiling and traveling above clogged and jammed lanes to points of obstruction (Fig. 7). Such electrically driven capsules, containing patrolmen knowledgeable in first-aid, and fully equipped with extensible ladders, stretchers, grappling hooks, and medical supplies, could reach a disabled vehicle on the road, render medical or other assistance, and lift or tow the vehicle to the first turnoff by means of the telescoping arms.

Access to Surface

Freight loading and pedestrian exits must be provided in abundance, since there are no surface exits to the inner city core from the underground system. Each building complex would have to provide large-capacity freight elevators directly to these docks and truck turnoffs. Moving stairs, ramps, and unattended passenger and freight elevators would service groups of buildings from the parking caverns by vertical elevator shafts drilled from below.

Lighting and Perception

Lighting intensity in the tunnels could vary gradually from very bright near the suburban exits and inlets to rather dim in the middle of the travel areas, letting the driver's eyes adjust to the variation and cutting down the lighting bill. Driver-stimulating murals might be considered to relieve claustrophobia, loss of perceptual awareness and monotony.

Wind and Weather

The absence of ice-melting salt sprays will be beneficial to automotive underbodies. The ventilation system should be designed to exploit the piston effect of all vehicles moving in a single direction in each tube and to save the motorist's fuel with greatly reduced windage losses.

Exhaust-Gas Processing

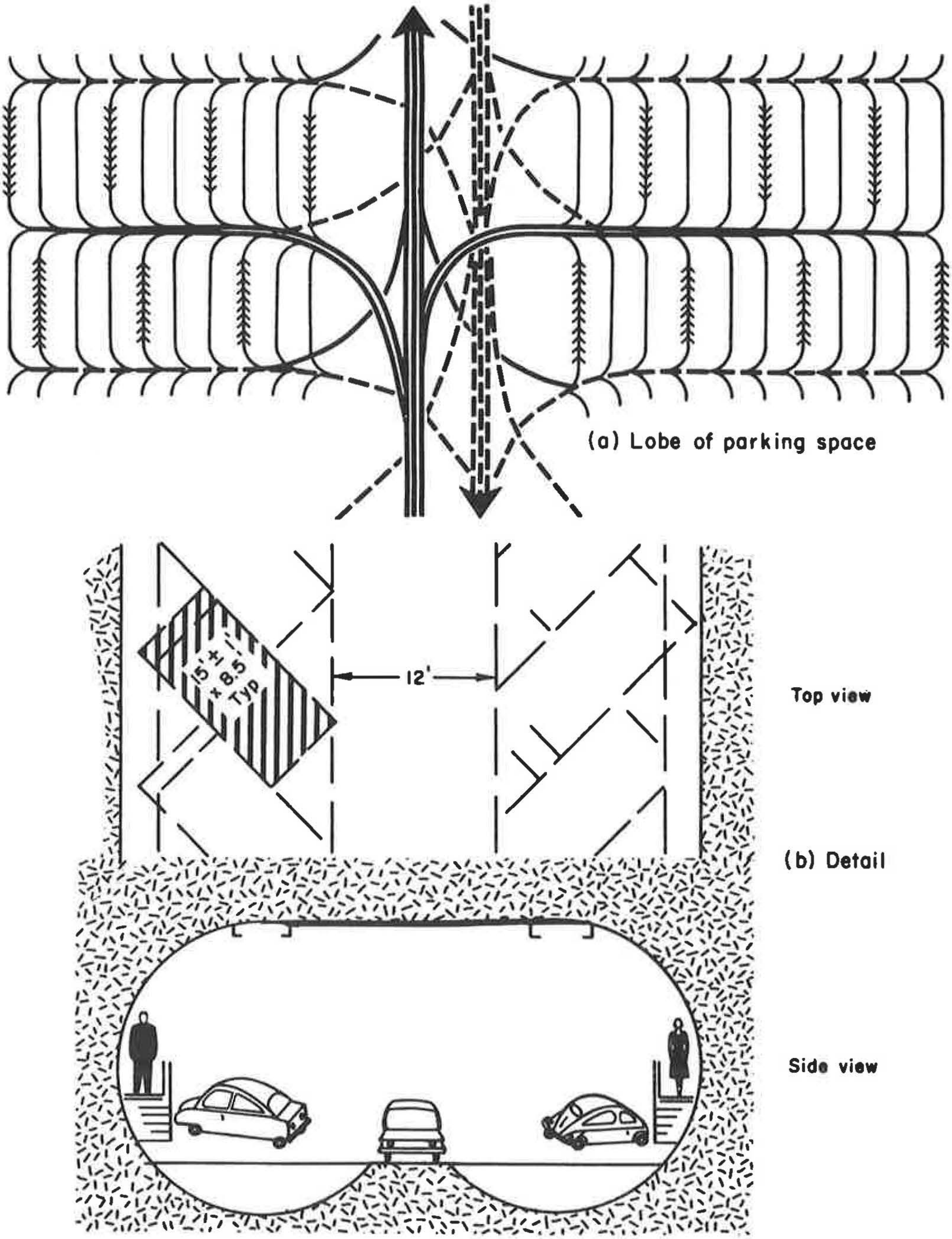
It would be technologically desirable to wash the ventilated air by water spray at the outlets, thus removing the water-soluble contaminants. Whatever insoluble pollutants are left (e.g., uncombusted hydrocarbons) could probably be removed quite profitably by standard waste product recovery schemes, such as appropriate filters, precipitators, and separators. The recovered tonnages of hydrocarbons might be startlingly high—enough perhaps for some enterprising private company to undertake the purification and recovery process.

Underground Parking Costs

Since parking spaces hundreds of feet under the CBD are connected only to the freeway tunnels as shown in Figure 9a, there would be no vehicular exits to the surface. Boring of parking spaces—a task as great as tunneling the roadways—should employ the same tunneling machines that would be used for the freeway. The schematic diagram in Figure 9 indicates that a million cars would require almost 1,000 mi of tunnel for parking, plus maybe another 500 mi of approaches, distribution roads, and interchanges for a total of about 1,500 mi. If such tunnels can be bored and finished for $3 million/mi, providing underground parking would then cost $4,500/car, requiring a daily parking fee of about $1.50 to $2.50.

High-Rise Garage Buildings

Multistory parking garages cost only $3,000/space, exclusive of land costs, to build, suggesting as a more economic possibility for large-capacity parking in the CBD a high-rise parking structure connected directly to the tunnels by being dozens of stories below as well as above ground.



(a) Lobe of parking space

(b) Detail

Figure 9. Underground parking space for small and compact cars.

A FEW EXAMPLES

Here we shall consider three cities, assuming that most mass transit riders into Los Angeles, Chicago, and Manhattan have acquired automobiles by the mid-1970's and insist on using them at all costs to commute to work. This is a purely hypothetical example and is the most extreme future concept that could be envisaged in the automobile-vs-public transportation debate. It provides an enlightening endpoint in calculating the cost and other aspects of total take-over by automobiles, taxis and trucks of all urban travel in the three largest metropolises in the United States. At the present time in Los Angeles, 80 percent of the trips to work are made by passenger car and the urban complex is closest to the "all out for cars" situation. In Chicago, only half of the trips to work are by car, and on Manhattan, only 8 percent of the work trips are by car or taxi. Tokyo would have been a fascinating example, since less than 0.5 percent of the million daily trips to the CBD are by auto.

A more detailed description of topics discussed here has been previously published (1).

Los Angeles

The population density patterns of Los Angeles mismatch the geology favorable to tunnels, requiring tunneling costs possibly higher than the $1 million/lane-mi assumed before. On the other hand, mass transit use in Los Angeles by the mid-1970's is the lowest per capita estimated in the three sample cities—at its optimistic best, a million riders per day, i.e., 500,000 round trips vs the recently estimated 700,000 riders per day.

A typical urban highway (such as the Congress Expressway in Chicago) can handle 12,000 veh/lane-day, averaging 1.8 passengers per car. With automotive evolution and population pressures, these numbers will be, by 1975, probably 14,000 veh/lane-day and 1.9 passengers per car; i.e., 27,000 persons per lane-day could penetrate subterraneously any area provided with sufficient parking space. This estimate agrees reasonably well with the projected number of 32,500 individuals per lane-day using the Santa Monica freeway by the mid-1970's.

Choosing a figure of 30,000 commuters per lane-day, the Los Angeles requirement in a dozen years would be 500,000/30,000 or 16.5 lanes in one direction plus perhaps another 7.5 in the opposite direction (assuming midday lane reversal), for a total of 24 lanes feeding into the elongated CBD of Wilshire Blvd., downtown, and Hollywood. It can be calculated that about 1,000 lane-mi would be required connected to 500,000 parking spaces under ground at $6,000/stall. The cost in Los Angeles of this additional transportation system would be ($$10^6$ to $$2 \times 10^6$/lane-mi) × 1,000 + ($6,000/car) × 500,000, or $4 billion to $5 billion, with two-thirds of the cost going into the parking spaces.

Chicago

The central Chicago district is penetrated in the peak morning hour or abandoned in the peak afternoon hour by about 200,000 individuals using public transportation. By the middle of the next decade, possibly ¼ million commuters may be riding mass transit vehicles in the maximum hour. When it comes to utilizing the Congress Expressway, Chicago car drivers seem capable of moving 2,000 veh/lane-hr under the best conditions and usually average very close to 2 passengers per vehicle. By 1975, then, accounting for trends in automotive development, some 5,000 individuals per lane-hour would be saturating the freeway's capacity.

Chicago's geological makeup is almost ideally suited for tunneling; throughout the basin, the bedrock is at the most only a few dozen feet underground, and the rock is well constituted for machine boring—soft enough to cut readily and strong enough to require minimal lining. Thus, we may conceive of the hypothetical transfer of all Chicago public transportation to individual automobiles and buses driven and parked underground.

Converging on the CBD might be 250,000/5,000 or 50 lanes one way and possibly 10 lanes the other way with midday lane reversal, for a total of 60 lanes into the center of Chicago feeding into ¾ million parking spaces. If this underground network were to parallel the present mass transit facilities and parking were provided to serve the present daytime inhabitancy peaks, some 1,300 lane-mi would be required (at a finished cost between $$10^9$ and $$2 \times 10^9$), plus $3 or $$4 \times 10^9$ for the parking spaces. Again, as in Los Angeles and Manhattan, parking room is the major component of the system in costs and bored space, amounting to two to three times the freeway tunneling costs.

New York

Under most of the New York City area there is competent bedrock, harder to bore than Chicago's bedrock but cheaper to line and repair. Many New Yorkers are conditioned to high-speed travel in tubes; traffic densities in the Brooklyn-Battery and Queens-Midtown tunnels even exceed the local bridge traffic experiences of 5 million veh/lane-yr, and occasionally automobiles have achieved the transportation of some 30,000 persons per lane-day assumed in an earlier example.

About 1.5 million people go to work in Manhattan; almost one million do so in the peak hour, and only 7 to 9 percent of these people use their automobiles or a taxi. Since about one-third of these workers reside in Manhattan proper, it may be assumed that only 1 million commuters might want to use their car to go to work—if given ample (but costly) roads and parking facilities close to their destinations—and could use some ½ million automobiles in their commuting trip. Projections for the next decade do not indicate a radical change in these numbers, indicating that the ½ million parking spaces that would have to be created would require about 800 mi of three-lane tunnels, costing \$2.5 to \$3.5 × 10^9—one-tenth of the cost of putting an American on the moon. Some 500 to 1,000 lane-mi would be required by 30 to 50 lanes and total system costs (parking and roads) would be between \$3 × 10^9 and \$6 × 10^9. This underground automotive system could be paid for by taxing each car about \$0.005 per tube-driven mile, plus a charge of \$2/day for downtown parking.

CONCLUSIONS AND RECOMMENDATIONS

A conclusion to be drawn from this study is that in the not-too-distant future it may be advantageous to place highways and parking hundreds of feet under the city core rather than on its surface or above it. Another conclusion is that the costs of providing all-automotive urban transportation and access to the central core are very high: though the multibillion dollar initial investment cost could be paid off by highway taxation and parking fees, the capital required for even a modest underground system is still well beyond the fiscal capability of local and state agencies. One may also conclude that only a major Federal agency could cope with the numbers, the cost-benefit considerations, and preliminary estimates of the economic attractiveness of urban land saving and reclamation, reduced construction costs, and increased income from renewed lane use, or exercise the engineering imagination and daring needed for testing the concept.

A final conclusion was that for every mile of new road into a densely inhabited area, a consistent requirement springs up for two or three times as much more area for parking. Since balanced planning would call for two-thirds of the total system cost to go to parking facilities, this might require a radical reorientation of the scope of highway agencies from primarily public road builders to include the role of public parking providers.

It is recommended that a thorough study be carried out of subsurface highways and parking, from the technical, cost-vs-utility, social, aesthetic, and institutional viewpoints. If such a study is to substantiate the promised efficiencies indicated in this analysis, it is also recommended that a design team of civil and mechanical engineers be given the task of developing and fabricating a three- or four-lane tunneling machine for hard rock. This boring machine should have integral provisions for fast and low-cost muck and broken rock removal to a prepared site, and for an automatic lining installer. A roadway installer would also have to be designed and constructed. This would keep pace with or be coupled to the tunneler, so that prefabricated half-tunnel-wide slabs could be emplaced at the proper rate.

On completion of the prototype tunneler, a car-critical urban site should be picked for a demonstration experiment. An eight-lane (two tubes) link between the Lincoln and Queens tunnels seems a most likely candidate, if a modest (e.g., 100,000 car) parking space without surface exits were jointly considered. The experience in boring, finishing, and operating this demonstration line might establish whether or not urban traffic of the future should be carried on the surface of our cities (and choke them with traffic) or underground and preserve them.

Our estimates of the price of these recommendations are as follows:

1. Feasibility study of deep underground highways and parking—less than $\$10^6$;
2. Design and fabrication of prototype tunneler—from $\$10 \times 10^6$ to $\$20 \times 10^6$; and
3. Trans-Manhattan connector and mid-Manhattan 10^5 -car park—less than $\$10^9$.

REFERENCE

1. Hoffman, G. A. Urban Underground Highways and Parking Facilities. RAND Corp., Memo. RM-3680-RC, Aug. 1963.