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BUREAU OF PUBLIC ROADS
U. S. DEPARTMENT OF COMMERCE
E. A. STROMBERG, Editor

Highway Transportation Economics

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PUBLIC ROADS takes pleasure in presenting this stimulating discussion of highway transportation economics by Richard Zettel of the Institute of Transportation and Traffic Engineering, University of California. It is certain to be of keen interest to layman, engineer, and economist alike.

It would require a weighty volume to detail exhaustively the maze of factors that complicate the problems of transportation economics. Many of the factors, as the author points out, are unmeasurable at present and may remain so. It is in the presentation of the problems of highway transportation economics that this article has its strength. Specific solutions are not offered. Indeed, there are no acceptable solutions to many of the problems that exist—at least, none to which all interested parties can now agree.

One of the basic difficulties, Mr. Zettel notes, is to get and retain perspective. What is the proper position of highway transportation in the total transportation field? How should highway costs be assigned among the various classes of motor vehicles, and what responsibility should be assumed by the general public as distinct from highway users? What are our highway needs today, and how shall costs and benefits be related? And what is the public willing to pay? How should highway needs be measured in relation to other needs for the general welfare?

Extensive research may eventually produce enough statistical data to permit derivation of theoretical solutions for some of these problems. But in the final analysis, as the author indicates, many decisions must rest upon collective judgment expressed through legislative bodies. It is hoped, of course, that research will whittle away at the edges of the imponderables and provide bases for sounder judgments which will reduce the imbalances and inefficiencies that may be present in our transportation system today.

As Mr. Zettel points out, we may take comfort from the fact that, despite all the difficulties and confusion, we have a complex yet effective and competent transportation system in this country. The effectiveness of the great productive machine that has made possible our high standards of living cannot be attributed alone to the wealth of our natural resources, the skill of our labor forces, and our efficient use of capital. It rests also, in no small measure, upon this remarkably capable transportation system which we have developed.

And highway transportation, all things considered, is perhaps the most important of all, the author believes. Not only is it a potent competitive force, but it complements all other modes of transportation and plays an indispensable role in the direct satisfaction of human wants. A continuation of the phenomenal progress of the past 50 years is one of the great challenges of the future.

Engineers, economists, and public-finance experts may not all see eye to eye with some of Mr. Zettel's theses and interpretations of available statistics, and publication of the article here does not signify that the Bureau of Public Roads necessarily vouches for it in entirety. The subject is so broad, so little explored, and so unsupported by facts, that lack of agreement is to be expected. Nevertheless, the reading of so thought-provoking a discussion cannot fail to stimulate all who have an interest in highways and transportation.

IN discussing a subject as broad as highway transportation economics it is necessary to choose the issues which seem, to the writer at least, to be most challenging. What will be attempted is a portrayal in broad outlines of the place of transportation in general, and highway transportation in particular, in the modern economy. Also to be pointed up are some of the broad economic issues which are of great concern to the public generally and should be of even greater concern to those directly connected with the transportation industry.

BASIC ECONOMIC CONCEPTS

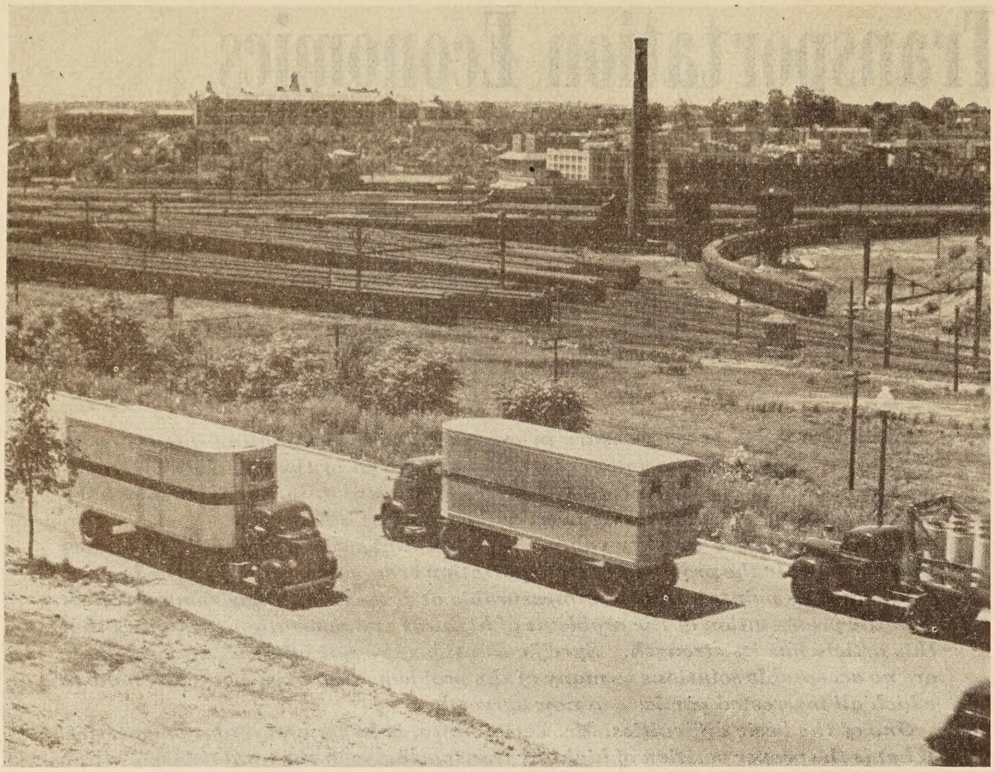
Economics is the study of the utilization of limited resources to satisfy human wants; it is a study of the production, distribution, and consumption of goods and services. It is basically concerned with the allocation of resources among the various uses to which they may be put. As we shall see, in the modern economy a considerable share of our economic efforts, of our labor, capital, and managerial ability, is devoted to supplying transportation service; and a considerable share of our incomes goes to pay for that service.

Transportation Fundamentals

Transportation service may satisfy human wants directly, as in the case of pleasure driving or vacation travel, or it may play a vital role in the productive process, as in the case of bringing raw materials to the factory and distributing finished goods to the market. In economic parlance, transportation adds place utility to goods and, hence, increases their value; otherwise it would not exist. These ideas may seem self-evident; but the significance of transportation's role in a progressive economy is not often fully appreciated. In fact, transportation is sometimes looked upon as a necessary evil, an unfortunate economic waste. Often neglected is the way in which an efficient transportation system increases our standards of living and contributes to our social well-being.

Consider for a moment the primitive American frontier town with its poor transportation facilities, and contrast it with the United States of today and its complex network of transportation. Only a moment's reflection shows that adequate transportation makes for a tremendous difference in the economy. Of course, transportation has always been vital, even in the primitive economy—even when it was pack-a-back. When early man learned to transport fish and game he improved his standard of living. Transportation meant economic progress. Until iron ore and fuel, not 10 miles apart, could be brought together steel could not be made.

Even today, one of the basic requirements for economic progress in the underdeveloped areas of the world is improved transportation, for the richest of resources have no value unless they can be moved, put into usable form, and then brought to the consumer. In a very real sense, the story of transportation is the story of civilization and economic progress. It is not surprising, then, that some have said the greatest invention of all time was the wheel. The anthropologist and the historian, the political scientist and the



A considerable share of our economic effort is devoted to supplying transportation services. (Washington, D. C.)

sociologist, frequently find explanations of institutional settings and cultural activities rooted in the prevailing transportation patterns of the times.

Transportation and Trade

Transportation is the prerequisite of trade. The travels of a Marco Polo, the explorations of a Columbus, were undertaken for purposes of trade, which presupposes transportation. Without improved transportation a community, or a nation, is limited to the goods it produces for itself. And transportation plays a more subtle role in our economy than merely permitting us to trade goods we have for those we have not.

Much of our modern economic progress may be attributed to regional specialization or division of labor, which tremendously increases our productive capacity by increasing efficiency and making large-scale manufacturing possible—both by bringing together the materials needed and by distributing the products to expanded markets. Consider the steel industry of Pennsylvania, citrus production of California and Florida, cotton and tobacco raising in the South, lumbering in the Northwest, the automobile industry of Detroit—and reflect on whether any of these would have been possible without improved transportation.

Transportation and Prices

Transportation serves a useful function in equalizing and stabilizing prices. Improved transportation effectively stays the development of local monopolies. It assures that a crop failure in one area will not bring disaster, for foods from other areas can be imported. Improved transportation increases competition, for when prices in one area are raised above the cost of production in another area plus the cost of transportation, products will be imported. An important feature of our economic system, directly related to the adequacy of transportation, is the extent of healthy competition that takes place between suppliers at the fringes of market areas. (Delivered price arrangements and basing-point systems involving conditions of monopoly, oligopoly, or monopolistic competition present issues which are not considered here. It is sufficient to say they do not vitiate, nor detract from, the main thesis presented.)

Transportation and Land Use

Transportation has a profound effect upon land uses and values. Some figures of the 1850's are available showing that a farmer would receive $48 a ton net for wheat if his land was only 10 miles from the major market, but the net price to a farmer 300 miles away would be only $4½—less than 10 percent as much. The difference was the cost of transportation by road. Now, if the direct costs of producing wheat at the "distant" point exceeded $4½ a ton, land there would have had no value for wheat production. However, if the direct costs were $2 at both points, land rent (for an acreage on which a ton of wheat could be produced) would have been $46 per ton at the closer point as compared with $2½ at the distant point. The value of the closer land would have been more than 18 times that of the distant land.

Today, fertile lands in many areas of the world still stand idle because of prohibitive transportation costs. A reduction in the cost of transportation would tend to increase land values in the remote regions but, at the same time, more land would be brought under cultivation and prices would tend to fall.

Many interesting phenomena in land use can be explained by analysis of transportation conditions. In the early days, whiskey production became an important industry west of the Alleghenies; it was too costly to ship wheat except in bottled form. Illinois and Iowa both produced great quantities of corn, but hog-raising became a much more extensive industry in Iowa; while it was profitable to ship corn to market from Illinois, the higher transportation costs from Iowa made it necessary to convert corn to meat prior to shipment.

Examples of the profound and generally beneficial economic effects of improved transportation are almost limitless in number and variety. For instance, urbanization and the later phenomenon of suburbanization would have been impossible without adequate transportation. The main point to be emphasized, however, is that good transportation serves to reduce the costs of production, even though it is itself a cost of production.

Passenger Transportation

A comment or two should be added with respect to passenger transportation. That large portion which is indulged in for business purposes is subject to the same economic considerations already suggested. For example, it permits a greater technical division of labor and thereby promotes efficiency in production. On the other hand, personal transportation for pleasure is consumption—the direct satisfaction of human wants. As in the purchase of any other goods or service, the public interest is to get it as cheaply as possible.

A General Conclusion

What has been said is intended primarily to establish not only that transportation is indispensible in a progressive society, but also that any lowering of the costs of transportation is good for the general economic welfare. Transportation is one of the costs of production. Whenever any of these costs is reduced our economy is strengthened; our standards of living can be raised. It is vitally important, however, that we bear in mind a clear concept of economic costs. By lowering the costs of production we mean either (1) producing the same amount of goods and services with a lesser expenditure of economic resources—labor, capital, and land, or (2) producing a greater amount with the same expenditure. From this it follows that when we appraise the costs of transportation service we must include all of the economic costs. It matters not whether the costs are met publicly or privately. Unfortunately, a prevalent tendency in some quarters is to ignore such costs as highway improvement, navigation development, or airport provision when they are paid for by government—a subject about which more will be said.

'ODAY'S TRANSPORTATION SYSTEM

We have in this country a highly developed nd extremely complicated system of domestic ransportation, consisting in the main of railoads, waterways, highways, pipelines, and irlines. A few figures, taken more or less at andom, indicate the significance of transporation in the United States. In 1950 it was stimated that intercity freight traffic mounted to 1,017 billion ton-miles. That gure may mean more if we realize that we noved in intercity transportation 1 ton of reight about 6,800 miles for every man, voman, and child in the country. In the ame year, our people traveled an estimated 00 billion passenger-miles in intercity movenent—the equivalent of 2,600 miles for every erson. The movement of people and goods vithin cities adds substantially to these gures.

We have built up a tremendous private and ublic investment in transportation facilities. More important, however, is the amount we re expending annually for transportation. The figures are astounding. It is estimated hat expenditures for personal transportation n 1950 totaled almost $23 billion—almost 12 percent of our total consumption expendiures—and that figure does not include any xpenditures for transportation service that vas incorporated in the prices of things we ought. The combined freight revenues of Class railroads and Class I motor carriers of property lone was in the neighborhood of $12 billion n 1950. For the development and promotion f all kinds of domestic transportation the Federal Government alone is spending about billion dollars annually. We need not oncern ourselves too much with figures of his sort. But we should realize that about ne-fifth of our total national effort is being xpended for transportation service—an appreiable slice of the national economy.

Highway Transportation

Of particular interest in this discussion is ighway transportation. The motor vehicle as virtually revolutionized the industry. Barely more than 50 years ago one of our eading economists could say: "The road sysem as a matter of national importance is a hing of the past." Today in excess of 50 nillion motor vehicles—9 million of which are rucks and busses—are operating on our highvay plant. In 1950 we traveled more than 37 billion passenger-miles and carried 126 illion ton-miles of freight over the highways etween cities. We consumed almost 36 illion gallons of motor fuel on our roads and treets. We had about one passenger car for very 3.7 persons and more than one truck for very 18 persons in 1950.

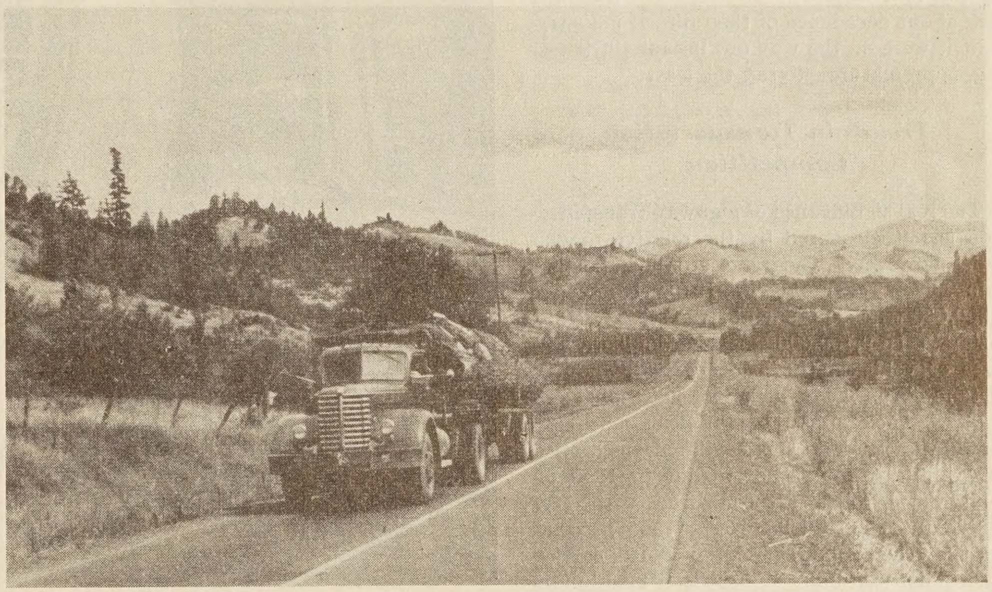
The magnitude of finances involved is peraps more important. Retail sales of autonobiles and automotive products exceeded 26 billion in 1948—more than 20 percent of ll retail sales in the country. It has been stimated that the total annual cost of highvay transportation is somewhere in the neighorhood of $40 billion—about one-seventh of he gross national product. One worker out of seven is employed in some phase of highway transportation.

Total expenditures for highways are almost as astonishing. We are attempting to maintain and improve a road and street plant of more than 3,300,000 miles. In this effort we have spent more than $60 billion for highway construction and maintenance in the last three decades. In 1950 we spent more than $4 billion for highway purposes, of which $2.4 billion was for construction and rights-of-way for State highways and local roads and streets. We collected more than $2.6 billion from highway users in the form of State road-user taxes, and large additional amounts in Federal excises and other general taxes.

Competition in Transportation

Highway transportation has changed a situation of virtual monopoly to one of very considerable competition. The competitive relations among carriers are a matter of basic interest to the economist. It is difficult to get a good grip on this problem, however, for each of the carrier groups has distinctive characteristics. In important areas they are complementary rather than competitive. For example, trucking within cities does not compete with rails or other modern forms of transport. Most trucking from farm to market or railhead is not competitive. Even if certain goods are moved by rail or water or air one time or another, at some time—probably many times—during the flow from producer to consumer the goods are moved by truck. Many such movements are not competitive.

Yet there is no doubt that truck transportation is making serious inroads on rail transportation. In 1950, trucks hauled 12.4 percent of the total ton-miles of intercity freight. The rails hauled 60.4 percent, and water, air, and pipelines accounted for the rest. As between trucks and rails, the



Transportation service brings raw materials to the factory (secondary road in Oregon) . . .

. . . and distributes finished goods to the market. (Maine Ave., Washington, D. C.)

percentages were 16 for trucks and 84 for rails.

The railroads themselves recognize that only a fraction of all trucks are actually competitive. They developed figures for 1948 indicating that only 400,000 of the more than 7 million trucks then in operation—those they called the "highway freighters"—were truly competitive. However, it was also estimated that these vehicles carried about 72 percent of the intercity truck traffic freight ton-miles. This would indicate a total of about 63 billion ton-miles. In the same year, the rails carried 643 billion freight ton-miles—over 10 times as much.

To carry all of the freight traffic in trucks, assuming it were at all possible, would seem to require about 4,400,000 "highway freighters." One may wonder what sort of highway system would be required to accommodate 11 times as many large motor freight carriers as we now have. But all this is mere speculation because there are sound economic reasons why trucks could not handle all the bulk, low-value, long-haul traffic that is today moving by rail and water. It would seem that any talk about decadence of the railroad industry, as if it were on the way out because of trucking, is premature—to say the least.

Trends in Transportation Competition

The real significance of highway transportation is not measured by the relative magnitudes, however. The trends are the important thing. For example, in 1940 there were 4,900,000 trucks on our highways. The 1951 estimate is 9,100,000—nearly double. The sizes of vehicles, the loads carried, and the distances run have also increased phenomenally. The Bureau of Public Roads estimated that loaded truck combinations carried 91.4 billion ton-miles of freight in 1950 on main rural roads, as compared with 13.7 billion in 1936—an increase of 565 percent. On the other hand, single-unit trucks carried 14.3 billion ton-miles in 1936 and 29.6 billion ton-miles in 1950, an increase of 107 percent. Average weights of loaded combinations on the main rural roads increased 55 percent between the 1936–37 period and 1950; average weights of loaded single-unit trucks increased 11 percent in the same period.

Here is another important trend. The revenues of steam railways were $4,050 million in 1939 and $9,587 million in 1950, but the revenues of motor carriers of property subject to regulation of the Interstate Commerce Commission increased from $792 million in 1939 to $3,737 million in 1950—an increase of 372 percent for trucks as compared with 137 percent for rails.

A matter of grave concern to the railroads is the fact that rail revenues went down significantly in 1945 and 1946 but in these years motor carrier revenues continued to increase. Again, in 1949 there was a significant 11 percent drop in rail revenues from the preceding year, but the revenues of motor carriers of property increased 8 percent.

One of the important facts revealed by the comparative data is this: Although ICC regulated motor carriers of property in 1948 hauled only 6.6 percent as much freight as rails in terms of freight ton-miles, their revenues were 34.7 percent as much as the rails. In 1950 Class I motor carriers received about 5.2 cents per ton-mile as compared with about 1.3 cents for rails. Thus, it is clear that truck traffic is considerably more remunerative than rail traffic on a freight ton-mile basis.

Now, there are several reasons for this. In general, motor carriers carry more valuable, higher-rated commodities; rates for less-than-carload traffic are higher than for carload traffic; rates for long hauls are lower on a ton-mile basis than for short hauls. To the extent, however, that trucks drain off the cream of the traffic, the problem of the rails is intensified, for they are left with the less remunerative traffic which may little more than cover out-of-pocket costs. A continuation of this trend would have a serious impact on the rate structures and financial stability of rail carriers.

Savings in operation may justify substantial investments in highway improvement. (Eastshore Freeway, California)

Advantages of Highway Transportation

Little time need be spent here in exploring reasons for the phenomenal growth of for-hire highway transportation. Its obvious advantages are flexibility and adaptability and these add up to economy and speed. Of the two, speed—the time elapsed from initiation of the shipment to delivery at the destination—is the more important in many current situations, for time in transit can be quite costly to both consignors and consignees. More rapid transport has fostered the smaller inventory policies of many businesses and has resulted in substantial interest savings. Another of the inherent advantages of highway transportation is the ability of the motor carrier to adapt the size of the vehicle to the shipment, thus making the industry especially capable of handling less-than-carload freight expeditiously. Door-to-door service, less handling of goods, lower packing costs, are among the many other factors that contribute to the success of the trucking industry.

Another factor partly responsible for the initial success of trucking was certain rate-making policies that had been well established while rails had a near monopoly of the traffic. For example, predominant emphasis on value-of-service rather than on cost, in fixing rates, and preferential treatment of long-haul over short-haul traffic, provided a situation in which a new group of carriers, already having certain inherent advantages, could rather easily attract a substantial amount of the more remunerative business. Not to be overlooked, also, is the fact that the motor vehicle provided an opportunity for producers to haul their own goods whenever rates seemed out of line or it seemed convenient to do so. The significant fact is that the development of highway transportation has transformed an industry of monopolistic characteristics to one of intense and effective competition—a condition that the general public and policy makers have been somewhat slow to recognize and appreciate.

An outstanding feature distinguishing highway from rail transportation is the public provision, financing, and management of roadways for motor vehicles. This has made it possible for many thousands of operators to enter the transportation industry. One truck or bus is all that is needed to set up in business. The result has been not only competition between rails and motor carriers, but also intense competition among segments of the motor-carrier industry; and hanging over the entire public-carrier industry is the constant threat of private operation of motor vehicles by industrial and commercial enterprises. The motor-carrier industry, despite the development of a few large carriers, is still characterized by thousands of small operations, involving relatively small investments, and often managed on a family or individual proprietorship basis. Progress has been slow in adapting public policies to the realities of this new situation. The regulatory agencies and the courts are just beginning to discard the monopoly concept and come to grips with the problems of "regulated competition."

HISTORICAL ASPECTS OF THE HIGHWAY FUNCTION

The rapid development and wide-spread use of the motor vehicle, which has so enormously increased the capacity and efficiency of our transportation facilities and changed the basic character of our transportation system, has also brought with it a whole new set of problems, particularly involving questions of public policy.

The enormous growth of motor-vehicle use sometimes tends to obscure the historical significance of roads. But in any fair appraisal of highway transportation today, it is essential to bear in mind that highways were not provided publicly in direct response to the demands of the motor-carrier industry. Nor, for that matter, is the motor vehicle responsible for the initial development of the road plant.

An interesting story, fraught with both economic and social interest, can be traced in the evolution of roads from the footpaths of primitive societies, which followed animal trails, to the modern high-speed, controlled-access expressways of today. We can only mention in passing the network of roads developed by the Roman Empire which contributed much to its military and other successes; and, on this continent, the roads built by the Incas of Peru which not only surprised the European explorers who found them, but are regarded even today as substantial engineering feats in view of the physical and technological handicaps under which they were constructed.

Early English Roads

Among the interesting features in English road history is the extensive network constructed by the Roman conquerors between A. D. 43 and 407, about which one writer commented that no engineering work comparable was seen until the railroad era, and another said, the history of English roads is almost the history of how and why the Roman roads became the modern trunk roads.

Another English development, perhaps having current significance, was the spread of a system of private toll roads, called turnpikes, in the 18th and early 19th centuries. These roads were privately constructed under governmental authority and protection. As a result of more than 4,000 legislative acts, all of the main roads of the country became toll roads and there was great improvement of the general highway system. Here then, is perhaps the first example of commercial operation of the road plant, based upon the concept that highways are not merely of local interest but are so important to the users that special charges can and perhaps should be imposed for their use. Public dissatisfaction with the toll barriers led to a process of "disturnpiking" inaugurated in 1837 but not finally completed until 1895.

Early American Roads

As might be expected, road history in early America rather closely paralleled the English history of the times. The first half of the 19th century was mainly a turnpike era. In 1792 Pennsylvania chartered the Lancaster Turnpike Company which constructed the first macadam road in the country as a toll facility. The toll movement spread rapidly. New York had chartered 500 toll bridge and turnpike companies by 1836; Pennsylvania had 220 companies; New England was covered by a network of toll roads. (And some people today regard the toll road as a modern innovation!)

A great many speculative excesses and abuses as well as mismanagement of the toll roads led to financial failures, resulting in losses both to individuals and to States that had heavily invested in them. Toll roads began to disappear from the scene about the middle of the 19th century, not only because of mismanagement but also because first canal and then railroad building had captured the public interest. So it was that highway improvement and maintenance became an orphan, to be sadly neglected during the latter part of the 19th century. What little was done, was done by local government, often under a procedure by which the citizens were expected to work out their local taxes by working on the roads, a practice that was characterized by inefficiency but seemed to be rather enjoyed as a social event. It was under these circumstances that Arthur Twining Hadley (then president of Yale University) could say in 1900 that roads no longer had national importance.

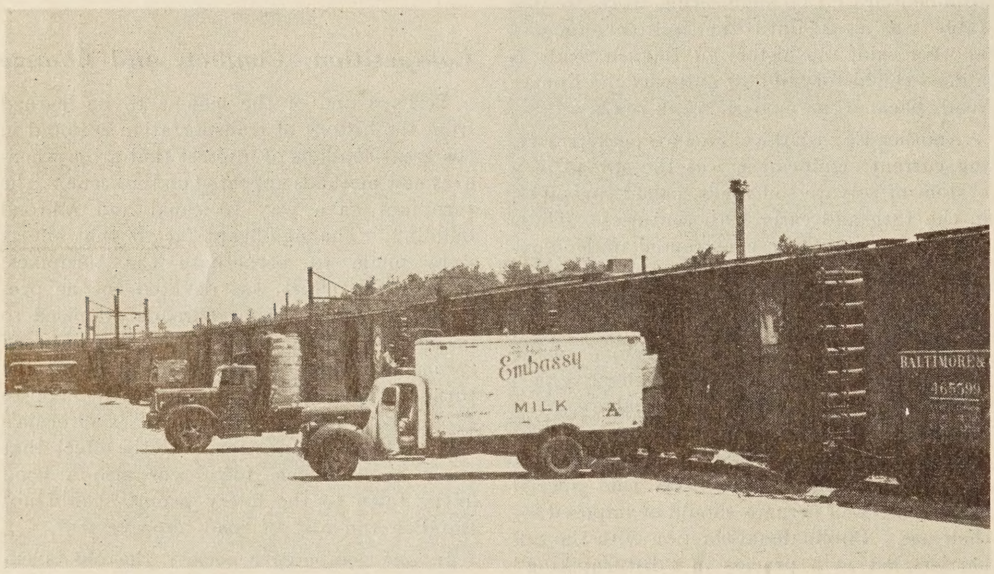
As a matter of fact, however, a good-roads movement was beginning to make itself felt in the late 1800's, before the automobile assumed any real importance. Railroad interests and bicycle manufacturers as well as farmers spearheaded the movement. But the real impetus was to come after the motor vehicle attained a significant place in the transportation scene.

Competition, Conflict, and Change

Perhaps one of the lessons to be learned from the history of transportation is found in the great conflicts of interest that arose whenever new methods appeared on the scene. The turnpikes gave way to canal and railroad building. The significant fact is that efforts were made to perpetuate the turnpikes; again much effort was devoted to the protection of canals when railroads promised to become a threat. Even the conflict between "wheelmen" and "livery men" at about the turn of the century was intense enough to evoke comment from one of California's first highway commissioners to the effect that every good bicycle town was also a good livery town so the livery people should not stand in the way of road improvement.

In our competitive society the old is expected to give way or to be modified by the new; it is to be expected, also, that vested interests in the old will resist change and bend every effort to protect themselves from new competition. Yet our economy is founded on change, however ruthless it may seem, for it is based on the principle that the exercise of intelligent self-interest nearly always advances the public interest. One who understands this will not be too surprised at the current campaigns of opposing forces in the transportation industry. He will understand why such fights often generate more heat than light and that the claims and counterclaims on all sides are frequently excessive. But even a dispassionate appraisal of the current situation will reveal that there are significant problems in transportation which do affect the public interest, even if they do not add up to the "crisis" one so frequently hears about.

The carrier groups are more complementary (Chicago airport) . . .



. . . than they are competitive. (Washington, D. C.)

THE HIGHWAY FUNCTION TODAY

The States today are managing what in effect amounts to one part of a full-scale transportation service. There has developed a partnership in transportation, not often fully appreciated, between government, which supplies the roadways, and private individuals and business firms, which supply the operating equipment. It is no easy task to coordinate these elements into an efficient transportation service. One of the great difficulties arises from the present-day conflicts of interest among various groups of users of the publicly provided road plant—for example, between truckers and automobile owners and among competing commercial highway users, such as common, contract, and private carriers. Additionally, there is the bitter controversy between motor carriers and other carriers, such as the rails.

In analyzing the transportation problem of today, one fact is worth remembering. The basic outlines of the American highway system were laid out long before any competitive threat of commercial motor-vehicle transportation to rails or other transportation agencies was realized. And the highway problem of today cannot be laid on the doorstep of the half-million heavy trucks that offer direct competition to other transportation.

The accommodation of more than 50 million other vehicles—passenger cars and complementary commercial vehicles—poses the basic highway problem. The freedom of movement, convenience, speed, and other featur of private passenger-car transportation whic have appealed to the American people an have led to the expenditures of a substanti portion of their incomes for highway tran portation are largely responsible for moder highway development. One evidence is tha of the 400 billion passenger-miles traveled i intercity movement in 1950 by all forms c transportation, almost 85 percent took plac in private passenger cars. Recognition of th situation, however, should not obscure th economically important fact that highway are multiple-purpose facilities which are use by many kinds of vehicles.

Economics of Joint Highway Use

The fact that highways are publicly pro vided and jointly used is perhaps one of th greatest economic advantages of highwa transportation. The road plant is supplied i response to numerous and varied demands We have, therefore, an outstanding exampl of the economies of joint use, on the one hand and the problems of joint-cost apportionment on the other.

To illustrate: A basic highway plant may b provided for passenger cars under any circum stances; if trucks are permitted to operate o the same highways and pay all special cost for which their operation is directly responsi ble, any additional payments they may mak go toward defraying the costs of the basi highway, and hence benefit all passenger-ca operators by reducing the costs of the basi highway to be apportioned among them.

Conversely, the truck operator who pays al of the direct highway costs assignable to hin is benefited by the tax contributions of pas senger-car operators that go to defray th overhead costs of the basic highway plant.

The point is that when different groups o users can use the same highway plant bot the total costs and the costs for each grou will be less than if each were required to sup ply its own facilities; provided, of course, tha each group meets all costs for which it i directly responsible and contributes somethin to defray the joint or overhead costs of th plant.

Perhaps a purely hypothetical example will help at this point. Suppose that a given stretch of four-lane highway adequate for passenger cars only could be constructed for $200,000. Suppose the same stretch could be built to accommodate both passenger cars and trucks for $240,000, and that a two-lane highway costing $140,000 would suffice for trucks alone. Now if two highways were built—one for passenger cars and one for trucks—the total outlay would be $340,000 as compared with only $240,000 for the single highway that would carry both kinds of traffic. The loss to the users—and to the economy— would be $100,000. Now if, for this single highway, passenger-car operators paid anything less than $200,000, they would save money. By the same token, if the truck operators paid anything less than $140,000 they, too, would save. Thus, if passenger cars were taxed $150,000 and trucks were taxed $90,000 each group of users would save $50,000 over what it would cost to supply themselves separate facilities. Here, then, we see clearly the economies of joint use.

Problem of Cost Assignment

But, at the same time, the example illustrates the problem of highway cost assignment. In the first place, it might be difficult to prove that it would cost $40,000 more to provide the highway for both kinds of traffic than for the passenger-car highway alone. And, if that hurdle is passed, the problem remains of apportioning the joint cost—that cost for which neither group can be held solely responsible—between them. Shall passenger cars be charged $200,000—the amount required for a basic highway? If so, the trucks would be charged only $40,000. Or should truckers be charged $140,000—the amount they would pay for their own highway? If so, passenger cars would be charged only $100,000.

The point is that anything the truckers pay over $40,000 helps the passenger-car operators, and anything the passenger-car operators pay over $100,000 helps the trucks. The complexity of apportioning joint or overhead highway costs among users becomes obvious. Even assuming that all direct costs have been ascertained and assigned to the responsible groups, all that can be said for sure is that truckers should pay at least $40,000 and not more than $140,000, while passenger-car operators should pay at least $100,000 and not more than $200,000.

Thus, to apportion the truly joint costs of the highway plant in order to fix reasonable user charges, we must turn to some theoretical basis such as relative use, differential benefit, or value-of-service. Naturally, there is much room for disagreement. The situation is tremendously more complicated in actual practice than in our example. First, we lack the detailed information necessary to ascertain to anyone's satisfaction the direct costs of the entire plant for which any particular group of users should be held responsible. Second, we are dealing with many kinds and sizes of vehicles, carrying all types of passengers and commodities, using different segments of the highway plant in varying degrees, operating different mileages during the year, and, by administrative necessity, subject to different kinds of imperfect user-tax bases.

Various Concepts of the Problem

The manifold problems involved in rationalizing and coordinating transportation service today are overwhelming. Anyone familiar with the subject would readily subscribe to the words of the late Director of the Highway Research Board, Roy Crum, when he said: "To visualize the whole picture at once has already given me mental indigestion."

One of the basic difficulties is to get and retain perspective. Not only among the directly conflicting forces are differences of opinion found. Many significant differences in approach to highway and other transportation problems are found among observers who presumably are impartial or at the least should not be passionately interested in the outcome.

For example, the highway engineer may be primarily interested in getting roads built to accommodate traffic; the competitive aspects of highway transportation do not trouble him; even the questions of wise allocation of limited economic resources or equitable taxation for highways are likely to be given short shrift.

The transportation economist, on the other hand, is likely to emphasize to the exclusion of all other considerations the competitive aspects of highway transportation and the effects on other carriers; private transportation, the prime generator of highway demand, may be virtually ignored.

The public-finance expert may fail to recognize the competitive aspects of highway provision and treat it as any other function of government, to be financed under the general tax system; he may see no merit in legal provisions against diversion to nonhighway purposes of taxes collected on a user basis; he is likely to advocate annual budgeting of highway funds in the same manner that all other funds are budgeted. He fails to appreciate what the transportation man sees or to recognize the engineer's demand for a reasonably steady and assured flow of income in order to permit long-range planning and orderly development of the highway system.

Such circumstances remind one of the parable of the blind men whose descriptions of the elephant differed so much because each had come into contact with different parts of its anatomy. If the experts do not see eye to eye, but get "mental indigestion" when viewing the whole transportation problem, is it any wonder that laymen have difficulty? Is it any wonder that our policy makers find little positive guidance in reaching the practical decisions they are inexorably forced to make?

Divergent Principles

Perhaps one source of difficulty in the management of our highway affairs lies in what Professor Shorey Peterson of the University of Michigan has called our "vacillating allegiance" to the divergent principles of the public economy and the private economy when confronted with various issues.

On the one hand, we are prone to treat highways like any other function of government. We do not distinguish taxes for highways from other taxes. We rely upon political judgment as to how much to spend for highways just as we do in determining how much to spend for schools or welfare. We also rely upon judgment as to how to distribute the cost, with little regard to the possibility of differential benefits to different groups or individuals. We justify expenditures in broad generalities, stressing the general welfare.

One unfortunate aspect of this approach to the highway problem is that we are left without any effective guides either as to the proper amounts and rates of investment in highways or as to appropriate methods and levels of taxation. Our sole criterion is how much we can collect from the taxpayers. When that has been determined, we must decide between many worthy but conflicting claims to the tax dollars on the basis of some vague, almost intuitive feeling of the effect upon the general welfare of alternative courses of action.

Operations in the private economy are, of course, governed by quite different considerations. Basically, the laws of supply and demand prevail. Goods are supplied in response to demand; the individual indicates the benefit he expects to derive from the various goods and services by the prices he is willing to pay. On the other side of the equation, goods and services are supplied if the prices offered will meet the costs of production—the costs of the factors, labor, capital, and enterprise, that go into them. Thus, in effect, the demand-supply equation becomes a benefit-cost equation. It has been suggested that principles applicable in the private economy can be adapted with appropriate modifications to serve as a guide in dealing with basic highway issues.

The motor carrier is adaptable to the commodity in shipment. (U S 1 north of Washington, D. C.)

A Modified Commercial Concept

As we have seen, with the exception of the comparatively brief experience with toll roads, the provision of highways was treated as a general function of government before the advent of the automobile. The development of the motor vehicle has modified our thinking. The extended radius of travel, the types of roads required, the magnitude of finances involved, the competitive aspects of highway provision in a private-enterprise economy, the need for standards governing the rate of highway investment, all conspire to give the highway function a much deeper economic significance than it formerly had. That the approach to highway problems in terms of the private economy has made headway is evidenced by the elaborate user tax systems founded on a benefit concept that have been developed and revised from time to time in all States. Further refinement and application of this commercial concept to highways may aid in solution of the perplexing problems of cost allocation and investment.

ALLOCATION OF HIGHWAY COSTS

It has already been suggested that the allocation of highway costs among the various beneficiaries is one of the basic issues in highway finance. One could engage in an involved and extended discussion here, which would lead deeply into the complicated and controversial subsidy issue. What needs to be emphasized is principle. There are good reasons why users should not be held responsible for all costs of all segments of the highway plant—a certain share should be assigned to property owners and general taxpayers. Once an assignment of responsibility to the highway users has been made, however, they should be expected to defray through user taxes all of the economic costs associated with highway provision.

The second difficult cost assignment problem is the determination of shares of responsibility to be borne by vehicles of different sizes and operating different mileages on the highway. Perhaps no other issue is so bitterly debated. On the one hand, one finds the claim that heavy vehicles are pounding the pavements to pieces; on the other, that properly built highways are unaffected by heavy vehicle use. At one extreme, it is contended that fuel consumption is a suitable measure of highway use; at the other, that weight and distance as reflected in the ton-mile is the best measure of relative highway use and, hence, of highway benefit.

Conclusive Answers Lacking

The very fact that there is so much dispute suggests that conclusive answers have not yet been found. This is the case. Various theories have been proposed for spreading highway costs. Just to name them—differential or incremental costs, relative use, value of service, differential benefits, differential space occupancy—is enough to suggest their complexity and diversity. It is perfectly clear that one cannot hope to find a formula upon which everyone can agree. For one thing, too little is known about highway costs. This may seem disconcerting in view of the fact that many billions have been invested in highways, but actually the problem is as much economic as it is engineering in nature.

Before we are too critical of this situation, we should recall that in many other fields where difficult overhead cost problems are met no precise solutions have been found. As one example, transportation rates for different commodities and distances are based largely on value of service—that is, what the traffic will bear—rather than on cost. All direct costs of providing transportation service have not been isolated and measured; even if they were, the large remaining portion would be truly joint or overhead costs that would have to be distributed upon some theoretical basis. Price fixing for highways is analogous to, and subject to the vagaries of, rate making for utilities.

There is, of course, a basic difference between private investment for profit and public investment, even when an attempt is made in the latter case to adopt certain principles applicable in the private economy. It is not to be inferred that the highway plant ought to be operated for profit. As in other monopoly situations, prices for highways might be fixed to maximize profits. However, it is well accepted that unregulated monopoly profits ought not be tolerated even in a private enterprise economy. Fixing charges for highway use is somewhat analogous to fixing rates for utilities where the purpose is not to maximize profits but to cover all costs plus a fair return on the investment. In various highway situations, of course, there may be a consumers' surplus in the sense that users would be willing to pay more than would be required to meet costs.

It seems clear that long-term research and more concentration of attention on the highway problem by people of diverse but relevant competences will lead to better solutions of the cost assignment problem than we now have. That the problem is receiving the interest it warrants is indicated by certain recent developments, among them being the creation by the Highway Research Board of a number of subcommittees "to bring about a frontal attack on this problem," each of which will deal with different phases of the question of equitable allocation of highway-tax responsibility. The Maryland test road and other studies to be operated are expected to provide useful data in this connection.

The essential requirement is that we focus attention on the costs of providing highways and strive toward the assignment of costs among beneficiaries on a rational basis. The goal toward which we press is to set the supply prices of highway service as they might be set in the private economy. When this is done in highway management and other fields where public aid is a factor, a realistic and economical basis for competition among the various transportation agencies will be established; and the rates of investment and distribution of traffic among the carriers will be determined by their relative economy and fitness.

THE MODERNIZATION PROBLEM

Perhaps one of the toughest public issues of the day concerns the appropriate rate of investment in the highway plant. We are informed by highway engineers, and indeed everyday experience tells us, that our highway systems are critically deficient in important respects. A Nation-wide campaign for better roads is under way, sponsored by important segments of the highway transportation industry. All evidence points to the fact that a considerably faster rate of highway expenditure will be required to bring the highway plant up to standards that will be regarded as satisfactory by the great majority of private and commercial users.

Highway Needs

It was estimated by the California Division of Highways last year that more than $3 billion would be needed to eliminate the State highway deficiencies that existed under 1950 traffic and cost conditions. Revenue estimates indicate that to do this job about $1.5 billion—only half enough—will be available by 1962, 10 years hence. And during this period traffic will continue to grow and probably will not generate enough revenue to meet the additional needs as they arise.

Owen and Dearing [1] have summarized the Nation-wide highway situation in these words:

> We have now entered a new era of highway development. This stage in the physical development of the highway system is characterized by technical standards and capital requirements that make previous concepts totally inadequate. Highway administrators are confronted with a situation analogous to that of an entire industry being overtaken by functional obsolescence. Survival depends on modernization; but in order to modernize, the old tools must be replaced and the entire plant redesigned.

In some quarters fear is now developing that a continuation of present highway inadequacies and the prospect of even worse conditions will have a serious impact upon motor-vehicle usage. The consequences would adversely affect the general welfare, not only because of the deleterious effect upon transportation efficiency, but also because of the effect upon manufacturers and purveyors of automotive products. As we have seen, an appreciable part of our economic prosperity in reasonably normal times is dependent upon highway transportation of all kinds. It might be observed at this point that the rails and waterways carry an appreciable amount of freight that is dependent upon a thriving highway transportation industry—not only finished products but also the materials that go into motor-vehicle production and highway building and use.

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[1] *Toll Roads and the Problem of Highway Modernization*, by Wilfred Owen and Charles L. Dearing. The Brookings Institution, 1951, p. 23.

There is conflict of interest among various road-user groups, but joint use is one of the advantages of highway transportation. (*U S 1 at Cottage City, Md.*)

Public Apathy

In spite of the evidence pointing to great highway inadequacy and a vague general realization of the fundamental importance of highway transportation to the national economy, there is considerable reluctance among the public to meet the issues squarely in the one way that really counts—additional financing. Perhaps an educational campaign with dramatic appeal and readily understandable arguments might dispel this public apathy. The fact is that a bare inventory of highway deficiencies, regardless of its size, does not in itself make a compelling case for additional financing or furnish a satisfactory guide either as to the aggregate amount that should be expended or as to the rate of annual expenditure that might be tolerable.

Time and again I have heard the heads of business state that their department heads or engineers can supply them with statements of needs and worth-while expenditures so large in the aggregate that they all cannot be financed, however much they might improve the operations. Almost every family can make up inventories of justifiable needs that add up to expenditures far in excess of their incomes.

The stark reality is that both the businessman and the family must adjust their expenditure programs to what they can afford out of current income or what they decide may be so essential as to justify pledging future income by borrowing. The businessman's decision is influenced not only by the demand situation as he estimates it, but also by the alternative uses to which he might put the limited capital available to him. The family must inevitably balance benefits from one possible outlay against benefits that would be derived from alternative expenditures.

It is not so with government in its usual operations. The government's power to tax gives it the power to adjust income to the expenditure program that is regarded as necessary or desirable. The crux of the problem is to determine what is necessary or desirable. Ordinarily there are no positive guides and so we rely on the collective judgment of the people as expressed through their legislators. But in the case of highways, that collective judgment may be influenced and perhaps improved if we can apply at least some of the standards and principles that would apply in the private economy. What is needed is an accurate evaluation of the benefits of improved highway service, and a realistic comparison of those values with the full economic costs of providing the service. This guiding principle is much easier to state than to apply, however.

Popular Appeal of Toll Roads

Perhaps one of the reasons that toll roads are attracting interest and active support in many circles is that a value-cost comparison is applied in a way that can be generally understood. The individual user can establish for himself a value-cost relation; before every trip he can weigh the benefits of using the facility against the toll charges. Ordinarily, the financial solvency of a toll facility is subjected to rigorous engineering and economic analyses before it is undertaken. In effect, the potential income depends upon the estimated demand for the service which, in turn, reflects the users' estimates of the benefits they expect to receive. This potential income must be sufficient to meet the costs of the project, including interest and an extra margin for the risk involved, before the project will be approved.

Unfortunately, no effectual way to apply this sort of value-cost analysis to the entire highway plant has been developed. Important applications of the value-cost ratios are made in determining relative merits of alternative highway investments in the effort to maximize benefits to the highway users. However, the problem is conceptually different from that under discussion here, for the money is already available for one highway improvement or another; the die is cast, the issue is not between highway expenditures and alternative unrelated public or private uses of the funds.

Without, at this time, judging the merits of toll financing under certain conditions, we may say that the basic highway problem does not permit solution by the erection of toll gates everywhere. This means that taxation must be used. As a general rule, however, highway taxes must be uniform throughout a political jurisdiction and must apply to everyone using any segment of the highway plant. What the people would pay based upon individual evaluations of the benefits if they had the choice of using or not using particular highway facilities will not be known as it is in the case of toll financing. But as a guide to policy it might be possible to approximate a hypothetical demand curve based upon an estimate of benefits that highway users might expect to derive from a particular level of highway improvement.

Measurement of Highway Benefits

One obvious clue to the measurement of benefits to users is the effect of highway improvements on the total costs of highway transportation. As a matter of fact, we are spending considerably less than 10 cents of our highway transportation dollar for the road plant. A larger percentage spent on highways may mean a lesser total cost. This is the real import of the thought that we pay more for poor highways than for good ones.

For example, savings in distance resulting from a highway improvement may result in savings in fuel and tire costs alone that will be more than sufficient to pay for the improvement. Less congestion, better road surfaces, reductions in grades all tend to reduce vehicle operating costs. In each case the benefits to the users can be reduced to monetary terms and offset against the highway cost.

Moreover, savings in time that may result from any one of a variety of highway improvements may have tremendous economic value even if we conservatively consider only the time of commercial and business highway users. The saving of 5 minutes may seem a small matter for one operator, but over the

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How shall costs be assigned among vehicles of different sizes, operating different mileages? (U S 1 near Newark, N. J.)

course of the year, during which thousands of vehicles are involved, the savings add up to enormous sums which, when compared with the highway costs, may justify very substantial investments in highway improvement.

The reduction in accidents that results from highway modernization also means lower costs for both commercial and private users, not only in the savings through elimination of accidents but also possibly through reduction of insurance rates.

In addition to tangible savings in operating, time, and accident costs there are intangibles to which, unfortunately, money costs cannot be attached—as, for example, the increased pleasure and comfort of the motorists on better highways. Undoubtedly these are benefits for which a great many motorists would also be willing to pay. It would seem proper, therefore, to reduce benefits to money equivalents wherever possible. But when the final decision is to be made, the intangibles must be evaluated by subjective judgment and may tip the scales in favor of higher level of improvement than might be indicated by monetary values alone. Here, then, after the technicians have completed their analyses, the collective judgment must come into play in reaching the final decision.

The Users' Willingness To Pay

Concrete evidence of the highway users' willingness to pay for improved highway service is found in the cases of certain toll roads in the East, where existing parallel non-toll roads are worn out, obsolete, or inadequate. Motorists usually pay about 1 cent per vehicle-mile for operation on these toll facilities—the equivalent of a gas tax of 15 or 20 cents a gallon in addition to their ordinary user taxes. Obviously the benefits of the higher type facilities, both tangible and intangible, as evaluated by the users themselves are substantial.

The case is even more striking when commercial and business uses alone are considered, for here the intangibles play a lesser role and the cold calculations of cost against value-of-service are dominant. Yet it appears to be to the advantage of the trucking industry to pay substantial tolls. For example, trucks are charged from 2 to 6 cents per mile, depending on size, for operation on the Pennsylvania Turnpike, yet about two-thirds of the revenue is derived from truck traffic. The reasons are apparent. Studies indicate, for example, that fuel consumption of a 50,000-pound gross-weight combination is 50 percent higher on an alternate route than on the Turnpike, and more than twice the time is required to travel the same distance on the alternative highway.

Problems of Estimating Costs and Benefits

We have alluded from time to time in this discussion to the need for including full costs in appraising the relative economy of highway transportation. Without further elaboration, it seems self-evident that all costs must be included in any value-cost comparison that is to be useful in solution of the highway investment problem.

It should be mentioned that this consideration is generally based upon the assumption of an economy of full employment. A departure from value-cost calculations, in the rigid sense, may be justified in a situation of under-employment. At such a time accelerated highway improvement may be considered an appropriate device to relieve unemployment and stimulate the economy. Even under such conditions, however, it is appropriate to maximize the benefits of highway improvement; on the cost side of the equation it will be appropriate to include less than the full monetary outlays (or perhaps calculate costs at zero) if, in fact, inflationary methods of financing are used which result in the employment of labor and other economic resources that would otherwise be idle. However, for purposes of comparing alternative public expenditures under such conditions it may be useful to develop benefit-cost ratios in which full monetary costs are included.

It should be emphasized that there are tremendous difficulties in the way of making a precise value-cost appraisal for the entire highway plant. Not enough is known about vehicle operating costs for different vehicles under different highway conditions. It is difficult to estimate the value of time savings for business and commercial users and debatable whether time savings for private users should be evaluated in money terms or regarded as an intangible. Placing an acceptable money value on highway accidents is no easy task, even if a satisfactory method of estimating potential reductions is agreed upon. Nevertheless, it seems clear that efforts should continue in this direction. It is to be hoped that continuing research will reduce the areas in which disputable assumptions or purely subjective evaluations are required.

Highways and the General Welfare

It may have been observed that these remarks have been confined to the benefits that accrue to the highway user. No mention has been made of the social and political values which are frequently ascribed to highways and emphasized in justifying an improvement program. The existence and importance of general benefits cannot be denied. But they do not lend themselves readily to specific economic evaluation. On the contrary, too much emphasis on general benefits may prove misleading. The basic problem under consideration is the diversion of limited economic resources from other possible uses to highways.

In many discussions of general benefits the fact is overlooked that the use of these resources for other purposes, whether private or public, may also render great general benefit to society. Almost every investment results in a general benefit. If it is said that highways aid the national defense, can it not be shown that a steel plant is also essential to the national defense? If it be said that highways weave together the social fabric, or promote political cohesion, or bring new lands under beneficial use, can it not also be shown that railroads or canals will render similar benefits? If general benefit were the basic criterion of Government expenditure, nearly all economic activity should be subsidized. To attempt to weigh the general benefits of highway provision against the general benefits that would be gained from any one of all the possible alternative uses to which the resources might be applied is a task almost incomprehensible in its sheer magnitude.

Yet it must be admitted that there are situations in which highway or other public expenditures may properly be found by collective judgment to be justifiable, even though they do not measure up under rigorous benefit-cost analysis. The benefit-cost approach is no panacea. To illustrate: The public purse has often been opened for the promotion and development of industry; perhaps in no field has its use been more generous than in transportation, starting with early road development and extending to canal building, land grants to railroads, development of inland waterways, and, continuing to the present, airmail subsidies and airport and airway development. Many roads are developed (and more are requested) which cannot be justified on a current traffic basis but which, it is hoped, will open new areas for profitable agricultural, mining, lumbering, or other development.

Quite obviously, the use of tax money for promotions of this sort must rest largely on collective judgment based upon such facts as can be marshalled regarding the future usefulness of an industry or a transportation agency or a newly developed area to the general welfare. Under such circumstances, it is obvious that any attempt to adopt standards applicable in the private economy must be abandoned. The problem is purely governmental in character; general benefit rather than benefit to individuals or identifiable groups of individuals furnishes the standard. It is inappropriate to raise revenue for such ventures through user charges; instead, general tax funds should be drawn upon.

Frequently it will be appropriate to use special assessments or property taxes to defray the costs of such highways, as in the case of streets in new subdivisions or roads in areas opened by reclamation projects. In other cases as, for example, access roads to military reservations, appropriations of general funds raised under prevailing tax institutions would seem appropriate.

Practical Expenditure Problems vs. Theoretical Cost Analyses

It would be nice if the value-cost approach provided a simple answer to the highway investment problems, but it does not. Not only must the question of highway justification on the basis of general benefits be dealt with under certain circumstances, as pointed out above, but other practical problems are encountered in the attempt to fix aggregate highway expenditures for the benefit of users on the basis of value-cost calculations. For example, it is quite proper to use true annual costs which include maintenance, depreciation, interest, and possibly taxes rather than expenditures in the comparison of value and costs. If highway improvements are financed through borrowing, or if, by sheer coincidence, annual depreciation on the highway plant provides adequately for new investment, a showing that benefits are greater than costs is useful.

But a pay-as-you-go system of highway finance, however desirable it may be on the basis of other considerations, may make benefit-cost comparisons virtually meaningless as a practical matter, particularly if the entire highway plant is in need of rehabilitation as seems to be the case today. The highway users are called upon to advance money to meet expenditures for improvements long before the expected benefits accrue. It is true that the inclusion of interest in the cost calculation theoretically solves the difficulty. But as a practical matter, the taxpayers are immediately burdened while the compensating benefits they will eventually enjoy are spread out over a considerable time in the future. Under such circumstances, a strong case for credit financing to spread the highway costs over time can be made.

More elusive is the fact that although interest clearly should be included in cost calculations for certain purposes, it is by no means certain that it should be included in tax charges levied for the use of highways that have been financed on a pay-as-you-go basis. This observation warrants much theoretical analysis that cannot be included here.

Previously mentioned was the fact that economists and engineers view the problems of highway finance from different perspectives. Economists would relate user charges to depreciation, maintenance, interest, and possibly taxes, so that the highway users would pay full economic costs for that portion of the existing highway plant for which they are held responsible and which they are currently using. In this manner, subsidy is eliminated. But engineers are looking to the future. They are interested in an adequate expenditure program to expand the highway plant to take care of existing and anticipated traffic conveniently and economically. The fact is that if only annual costs of the existing plant are met by users the only amounts available for expansion of the plant would be the imputed interest that might be included in ascertaining annual costs. If additional funds are secured by increases in user taxes, users would pay more than annual costs and there would be an overpayment—a negative subsidy.

The difficulty might be solved by borrowing or by the use of general tax funds for highway expansion. In the latter case, the popular notion that the use of general taxes for highways is clearly an indication of subsidy to users should be dispelled. However, the financing of a highway plant through general funds with subsequent repayment by user charges which include interest and general taxes, while conceptually sound in economic theory, would require a radical departure from present thinking about highway problems. It would raise another difficult policy question. Investment of general funds in the highway plant provided for benefit of users would be based, not upon the free choice of individuals, but upon collective judgment as expressed through legislatures and effected through compulsory taxation. What standard would guide policy-makers in determining how much current income or savings should be taken from individuals through general taxation and invested collectively in highways?

Favorable Benefit-Cost Ratio Not Conclusive

The practical problem of dealing in highway expenditures when actually financing highway improvements but dealing in economic costs in making comparisons with highway benefits raises other issues. Perhaps these can be illustrated by a homely example. Let it be assumed that accurate cost studies show that a home freezer will pay for itself over a period of time by direct savings in food costs, and that it will yield other benefits such as savings in shopping time. Establishment of these facts will not be likely to cause every family in the nation to rush out and acquire a freezer. We have suggested one reason: An immediate expenditure is required; the savings will accrue over a period of years. (Even if credit is used for the purchase, the time extended ordinarily will not be long enough to reduce payments to an annual cost basis.)

There is another reason. Each family has alternative uses for its funds. Suppose a family is faced with a choice between a freezer

Our street and highway systems are critically deficient in important respects. (Pratt St., Baltimore, Md.)

and a television set. The annual money costs may be the same. But the cost to this family of acquiring a freezer will be the value (anticipated benefits) of the television set which would have to be given up. In its judgment the television set may yield greater benefits than the freezer, even though it has been proved that the freezer will pay for itself over time.

The import of this observation is that costs as computed in highway benefit-cost calculations for investment analysis may be understated. It might be assumed that highway improvements will be justified when the benefits gained, evaluated in monetary terms, exceed the costs. But a home freezer also may yield benefits that exceed its cost. Just as the family might choose a television set instead of a home freezer, given a choice it might choose either of these instead of highway improvements, even though the latter was shown to yield benefits in excess of costs.

Similar considerations might apply in business situations. Highway improvements may result in savings which over time more than offset their cost for a particular trucking firm. But suppose the firm could gain even greater savings with a similar outlay for modernizing its fleet of vehicles. This would be the more prudent investment, if the firm had any choice.

Again, consider the total economy. Suppose it is proved that a given investment in highways yields benefits that far exceed costs. But society as a whole has alternative uses for its economic resources. And value-cost calculations for a reclamation project may also show benefits exceeding costs. How will the choice be made between the highway improvement and the reclamation project? Perhaps if there were only two alternatives an answer could be devised. But a formula to choose between highway improvements and all other possible uses, both private and governmental, both productive and consumptive, to which the limited resources might be put would be virtually incomprehensible.

Judgment Is Involved

It is clear, then, that benefit-cost analysis is subject to severe limitations, at least in the present state of knowledge. Individuals, businesses, or society as a whole may well find that highway improvements, despite favorable benefit-cost ratios, are less desirable than alternative uses of the resources. In the final analysis, the decision on aggregate highway investment must rest upon collective judgment expressed through the legislature. This is not to say that benefit-cost analysis serves no purpose. Quite obviously, if benefits are less than costs, highway expenditures would not be warranted. But where the benefit-cost ratio is favorable, subjective judgment must come into play. The higher the ratio, the more convincing is the case for highway expenditure. But at some point on the scale, perhaps a cut-off should be established. That point could only be determined by intersubjective agreement.

We have entered a new era of highway development. (Approaches to Harbor Drive, Portland, Oreg.)

Our discussion has been confined to benefit-cost calculations as a possible criterion for highway improvement programs. An approach to the problem, now widely discussed, is based on an engineering evaluation of the sufficiency of various segments of the highway system, each segment being given a rating in relation to an adequate engineering standard. But unless all roads are to be brought up to the adequate standard, a point must be selected below adequacy which can only be determined by subjective judgment. A possible guide in making this judgment is a comparison of highway benefits with costs at various points on the sufficiency rating curve.

The fact that no formula has yet been devised to grind out a precise answer to the problem of highway investment is not surprising. Wherever economic choices are required, individual or collective judgment is involved. In the private business world, final decisions between alternative courses of action rest upon judgment of the head of the business or the board of directors. The economic decisions of the individual, the family, the business, and the government need to be buttressed by facts. One of the basic aims of economic research should be to supply the facts and make the analyses that will lead to more rational decisions.

With respect to highway finance, there may be no substitute for informed judgment, but as an initial step forward we need merely obtain public recognition of two basic concepts: (1) that highway transportation efficiency and economy depend upon both the public roadway and the private vehicle, and (2) that highway expenditures should be evaluated by weighing benefits against cost, and not as government largess. The results cannot fail to be salutary.

CONCLUDING OBSERVATIONS

Surely by now it must be clear why a contemplation of highway transportation economics is enough to give one "mental indigestion." We may take comfort from the fact that, despite all the difficulties and confusion, we have developed a remarkably effective and efficient transportation system in this country. There is every reason to believe that further progress will be made. Competition will continue; there will be shifts of traffic; the old methods will give way to the new; and over-all efficiency will increase. It is perhaps inevitable in the competitive system, particularly when complicated by varying degrees of governmental participation, that inefficiencies and imbalances will be found when comparisons are made with theoretically ideal conditions.

There is no easy way out of the difficulty, for it is apparent that the fundamental issues would remain, and perhaps be greatly exaggerated, even if our transportation agencies were unified under complete government control. Fortunately, we can afford to tolerate some economic losses to gain the greater advantages that accrue under the stimulus of competition which leads constantly to new developments and improvements. It is to be hoped, of course, that further research will whittle away at the edges of the imponderables and provide bases for sounder judgments that will reduce the imbalances and inefficiencies that may be present in our transportation system.

It bears repeating that the effectiveness of the great productive machine that has made possible such high standards of living in this country cannot be attributed alone to the wealth of our natural resources, the skill of our labor forces, and our efficient use of capital in mass production. It rests, also, in no small measure, upon the complex but remarkably capable transportation system that has been developed. And highway transportation, all things considered, is perhaps the most important of all. Not only is it a potent competitive force, but it complements all other transportation agencies and plays an indispensable role in the direct satisfaction of human wants. A continuation of the phenomenal progress of highway transportation of the past 50 years is one of the great challenges of the future.

Reaction of Aggregate with Low-Alkali Cement

(Continued from page 56)

As indicated by Davis, Stanton[5] made several references to the effect of small amounts of alkali–reactive aggregates on the expansion of mortar, and to the possibility of a relation between the amount of the alkali and the amount of the reactive aggregate. In his reply to comments regarding his paper in the 1942 Transactions of the American Society of Civil Engineers, Stanton states:

> Further attention is called to the low percentage of opal required for maximum results, as well as the remarkably low percentage (in some cases less than 0.5 percent) which produces excessive expansion in a relatively short time * * *.
>
> Test results available by July 1940, led to the conclusion that, since little, if any, measurable expansion was observed with deleterious particles below 80-mesh or 100-mesh size, the reason for the falling off in expansion as the percentage of such particles was increased beyond a reasonable percentage might be an accelerated reaction between the cement and finely dispersed mineral particles.
>
> Although the underlying cause may be that originally suspected, later tests showed that neutralization also occurs in the presence of excess percentages of coarser particles from which all finer particles have been removed. From this it would appear that, for maximum reaction, there is a relation between the amount of reactive mineral in any unit area and the alkali in the cement * * *.

In connection with a discussion of the effect of added sodium or potassium hydroxide to mortar or concrete, Stanton also states:

> It is probable that there is a different "pessimum" amount of alkali for various minerals, just as there is a different "pessimum" amount of different minerals for a given alkali content.

It is unfortunate that Stanton did not inquire further regarding the behavior of aggregates containing small amounts of reactive material or develop the relation between the amount of reactive mineral and the alkali in the cement more fully. Lack of definite information along these lines as well as incomplete knowledge of the behavior of low-alkali cements has caused the development of certain assumptions regarding high-alkali cements and highly reactive aggregates which may be entirely unwarranted.

Application of Findings

The application of these findings to the apparently anomalous results obtained in many previous investigations will readily be seen. Specific mention of only one of these investigations will be made. It will be recalled that in a study of the behavior of Platte River gravel as a concrete aggregate, Jackson and Kellermann[6] reported that the gravel was found to contain only 0.3 percent opal by weight. This small amount of opal was believed by many to be insufficient to cause distress of concrete, yet concrete pavements prepared with this gravel persistently developed multiple cracking and excessive expansion. From the information shown here, the use of an aggregate containing very small amounts of opal may be sufficient with a particular cement to cause distress of concrete due to internal expansion.

In determinations of the availability for chemical reaction of alkali in portland cement, it seems to be highly desirable to make tests of mortar using sand containing several different amounts of reactive mineral. The data given here show that determinations should be made of the quantity of reactive material which will give the maximum amount of expansion with the particular cement under test. Only by this method can a worth-while comparison of the chemical activity of different cements be obtained.

If concrete is prepared with a low-alkali cement, there is no surety that a nonexpansive material will be obtained unless the aggregate contains no reactive mineral or sufficient reactive mineral to give a low value for the alkali–reactive aggregate ratio. In the case of high-alkali cement, the addition of a small amount of reactive matter to the concrete to control the reaction may cause the development of more expansion than if the reactive matter were omitted. In either case, it is believed that tests should be made using the cement, the aggregates, and the admixture, if any, which are considered for use in the proposed construction. Only by the preparation and testing of concrete as it will be used can information of the stability of the material be obtained.

[5] See footnote 2, p. 50.

[6] *Volume changes in sand-gravel concrete,* by F. H. Jackson and W. F. Kellermann. Proceedings of the Highway Research Board, vol. 22, 1942.

Reaction of Aggregate with Low-Alkali Cement

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported by DONALD O. WOOL
Senior Materials Enginee

Abnormal expansion of concrete, with resulting damage, has been widely observed for a number of years. Previous study of this phenomenon has disclosed the cause to lie in the reaction of alkali in the cement with certain reactive materials in the aggregate. It has generally been considered in the past that the amount of expansion was related to the alkali content of the cement—the larger the alkali content, the greater the expansion.

From the test data reported in this article, it now appears that excessive expansion of concrete is governed, not by the cement alkali content alone, but by the relation of the alkali content of the cement to the amount of reactive material in the aggregate. Low-alkali cement used with aggregate containing a small amount of reactive material may result in objectionable expansion, while the same cement with aggregate containing a relatively large amount of reactive material may have little if any reaction.

It is evident that, if excessive expansion of concrete is to be avoided, the alkali content of the cement and the amount of reactive material in the aggregate must both be investigated, and their reactive effect explored. Tests should be made using the cement, the aggregates, and the admixture, if any, which are considered for use in proposed construction. Only by the preparation and testing of concrete as it will be used can information on the stability of the material be obtained.

TESTS of 36 portland cements varying in alkali content [1] from 0.22 percent to 0.99 percent indicate, as reported in this article, that mortar prepared with any portland cement may develop excessive expansion due to the reaction between the aggregate and sodium oxide or potassium oxide, the alkalis in portland cement. An expansion of 0.1 percent or more at an age of 1 year or less is considered as an excessive amount of expansion. The quantity of alkali-reactive material in the sand needed to obtain a maximum reaction appears to be dependent on the amount of alkali in the cement. If the aggregate contains a relatively large amount of alkali-reactive material, a low-alkali cement probably will cause little if any reaction, but the same cement used with a sand having only a small amount of reactive material may cause an objectionable expansion. Definite information regarding the stability of concrete with respect to expansion caused by chemical reaction can be obtained only by tests of concrete containing the cement and the aggregates to be used, combined in the same proportions as specified for the work.

Previous Tests and Conclusions

In his first report [2] on the chemical reaction between cement and aggregates, T. E. Stanton concluded:

> The chemical reaction producing excessive expansion apparently occurs only when the portland cement component contains an appreciable percentage of alkali in the form of sodium and potassium oxides. It is of an intensity proportional to the percentage of such oxides, apparently being of such low order as to be negligible when the alkali content is less than 0.6 percent.

Stanton's use of 0.6 percent alkali to separate high-alkali from low-alkali cements has been accepted widely and the procedure developed by the laboratory of the California Division of Highways for the determination of reactive aggregates has been used extensively. Under this procedure comparisons are made between the expansion developed by a mortar containing a high-alkali cement (0.6 percent or more) in combination with the aggregate under investigation and the expansion of similar mortars containing the same cement and one or more standard aggregates of known behavior. These standard aggregates include a nonreactive sand (silica sand from Ottawa, Ill., is used by the Bureau of Public Roads), and reactive sands which are obtained by the addition to the nonreactive sand of small amounts of material containing opal. Several opal-bearing limestones and cherts were tested by the Bureau of Public Roads but different shipments of these materials were found to vary in their reactivity with alkali and the use of practically pure opal was adopted.

Data published by Stanton and data subsequently obtained by the Bureau of Public Roads showed that the expansion of portland cement mortar was influenced by the amount and grain size of the reactive material in the sand as well as by the particular cement used. In figure 1, the effect on the expansion of mortar of different percentages of reactive material in the aggregates is shown.[3] Information developed in the laboratory of the Bureau of Public Roads regarding the effect of size of grain of reactive limestone on the expansion of mortar is given in figure 2.

Stanton's tests (fig. 1) indicate that, in the case of chert, maximum expansion was developed when approximately 5 percent of the reactive material was used. On the other hand, when the reactive limestone was used, Stanton's tests showed that 20 percent was required to develop maximum expansion as compared with 10 percent in the Bureau's tests (fig. 2). As the result of this work, the Bureau of Public Roads adopted the practice of using, as a standard reactive aggregate, Ottawa silica sand to which was added 5 or 10 percent crushed opal by weight. At first, little consideration was given to the size of the crushed opal other than it pass the No. 8 sieve and be retained on the No. 50 sieve. Later, it was found that variations in the size of the opal caused nonuniform results from test to test, and the practice of using a single size of crushed opal was adopted. For use with Ottawa sand, the opal was sieved to the No. 16 to No. 30 size.

Failures with Low-Alkali Cement

In the earlier phases of investigations of the alkali–aggregate reaction, consideration was given almost entirely to determining if a particular aggregate could be used safely with high-alkali cement. Test specimens were prepared with the aggregate in question and

[1] Sodium oxide and potassium oxide are reported here as "total alkali" with the percentage of alkali given as the sum of the sodium oxide content plus 0.658 of the potassium oxide content.

[2] *Expansion of concrete through reaction between cement and aggregate*, by Thomas E. Stanton. Transactions of the American Society of Civil Engineers, vol. 107, pp. 54-84 1942.

[3] Taken from figure 2, *Durability of Concrete as Affected by Aggregates*, by Thomas E. Stanton. National Sand and Gravel Association Circular No. 28, 1947.

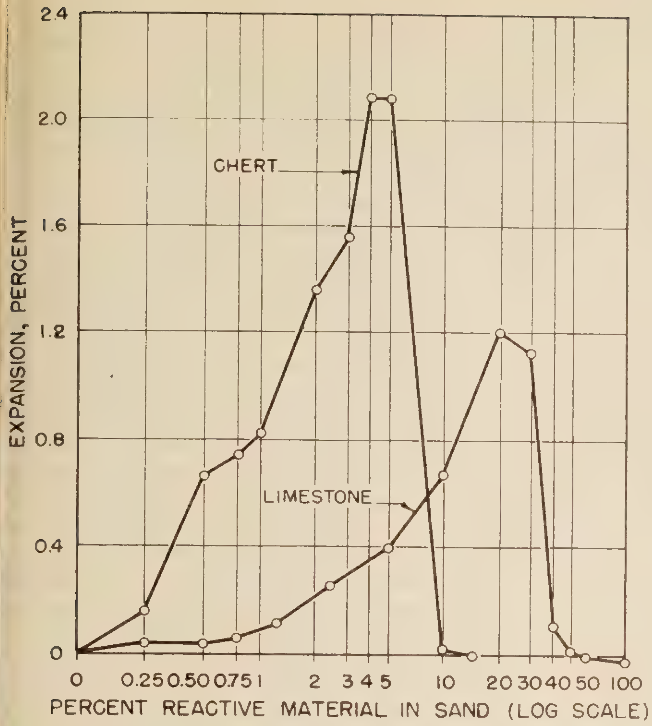

Figure 1.—Effect of amount and kind of reactive material on expansion of 1:2 mortar at age of 48 months. (Reactive material substituted for equivalent percentages of neutral sand; alkali in cement, 1.14 percent; mortar bars stored in sealed containers at 70° F. After Stanton.)

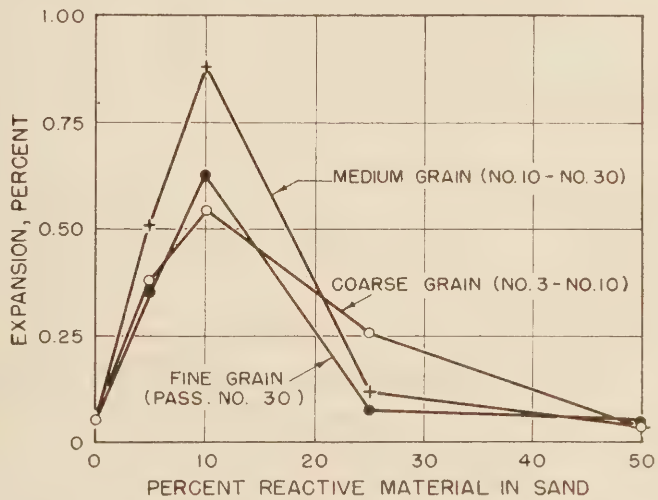

Figure 2.—Effect of amount and size of grain of reactive material on expansion of 1:2 mortar at age of 36 months. (Reactive siliceous magnesium limestone substituted for equal percentages of Potomac River sand; storage in moist air at 130° F.)

each of several high-alkali cements. Occasionally a low-alkali cement was also used, but the expansion of low-alkali cement mortar was usually so small that it was believed a waste of effort to test such material. When interest developed in possible differences in the activity of different high-alkali cements, the same belief of the nonreactivity of low-alkali cements prevailed and, except for an occasional token test, little thought was given to studies of low-alkali cements.

With broadening of knowledge of the occurrence of alkali–aggregate reaction in the field, reports were received of the failure of concrete containing low-alkali cement. In some instances the type of failure was reported to resemble that found when reactive aggregates were used with high-alkali cement. The receipt of this information recalled certain anomalies found in laboratory work with low-alkali cements in which excessive amounts of expansion of mortar had been observed. A review of the test records showed many instances where mortar prepared with low-alkali cement developed excessive expansion; in other work, mortars containing high-alkali cement and reactive aggregates gave only small amounts of expansion. The number of these results as well as several instances of duplication of materials used and duplication of results, indicated that possibly some features of the alkali–aggregate reaction had not been given the attention they deserved.

Available Data Restudied

These observations indicated the desirability of investigating more fully the behavior of the low-alkali cements in combination with sands containing small amounts of reactive material. Instead of initiating a new research project, however, it was decided to study certain available data from tests which had been under way for various periods up to 18 months. These tests involved determination of the expansion of mortar bars made with a large number of cements of varying alkali content in combination with aggregates containing very small percentages of opal.

A review of the data for this group of tests showed that 36 cements from 35 different mills had been tested with graded Ottawa sand containing 1, 2, and 5 percent of opal. Chemical analyses of these cements are given in table 1. Fifteen of the cements had an alkali content of less than 0.60 percent, and nine contained less than 0.50 percent alkali. Only one round of test specimens was made with ten of the cements, but two to five rounds, depending on the amount of material available, were made on different days with the other cements. Each round consisted of two specimens prepared with each of the three test sands. A water-cement ratio of 0.5 by weight was used for each mortar.

All specimens were stored in moist air at a temperature of 100° F., and determinations of change in volume were made at periodic intervals. Over half of the specimens were kept under test to an age of 18 months; tests of specimens prepared with the other cements were discontinued at earlier ages when an excessive amount of expansion was found. It is unfortunate that all specimens were not tested to an age of at least a year but the overcrowding of the storage facilities required the removal of some of the specimens. In the accompanying data showing expansion of mortar, the number of specimens used to obtain the values reported is shown. In a number of cases, breakage of a test specimen or discontinuance of tests for another reason caused the deletion of all test determinations for the specimens so affected.

Surprising Results Obtained

The results of tests for expansion of mortar are given in table 2, and are shown graphically in figures 3A and 3B. The results obtained show a surprising trend. All of the cements show more expansion when used with sand containing either 1 or 2 percent of opal than when used with sand containing 5 percent of opal. It has been known for some time that if sufficient opal were added to inert sand, a mortar could be obtained which would have little expansion. However, the amount of opal needed to obtain this has been believed to be 25 percent or more, and sand containing only 5 percent of opal was considered to be highly reactive. To find that smaller amounts of opal in a sand would cause greater amounts of expansion raises a question as to the validity of the results obtained in earlier investigations, particularly those concerned with the availability for reaction of alkali in cement.

At least one of the three mortars prepared with each cement expanded 0.10 percent or more at an age of 1 year or less. An expansion of this amount at an age of 1 year has recently been included in a proposed revision of the standard specifications for concrete aggregates, American Society for Testing Materials designation C 33, to indicate an aggregate which is objectionably reactive with alkali in cement. On the basis of this maximum permissible expansion, the results of these tests may be interpreted to show that

Table 1.—Chemical analysis and compound composition of cements (in percent)

Cement No.	Chemical analysis								Total alkali	Compound composition		
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O		C_3S	C_2S	C_3A
1	20.3	6.5	2.2	67.3	0.8	1.8	0.04	0.28	0.22	68	7	14
2	20.4	6.5	2.8	63.7	3.0	2.1	.14	.13	.23	50	21	12
3	22.1	5.9	2.0	65.6	1.0	1.9	.39	.08	.24	51	25	12
4	21.7	6.0	2.2	65.5	1.0	1.8	.09	.28	.27	53	22	12
5	21.3	5.9	2.9	65.3	1.2	2.3	.07	.34	.29	54	21	11
6	20.9	6.2	2.1	66.1	1.0	1.8	.08	.32	.29	60	14	14
7	19.7	7.1	3.2	65.1	1.3	2.1	.08	.42	.36	57	14	13
8	22.1	5.1	1.8	66.6	1.1	1.7	.32	.11	.39	61	17	10
9	20.5	6.2	3.2	65.2	.9	2.3	.15	.43	.43	57	16	11
10	----	-----	-----	----	----	----	.20	.47	.51	----	----	----
11	19.7	6.7	3.5	65.1	.9	2.1	.14	.59	.53	59	12	12
12	21.4	5.8	2.4	65.6	1.0	1.9	.15	.59	.54	57	19	11
13	20.7	5.7	2.6	63.6	3.2	1.6	.19	.53	.54	55	18	11
14	22.0	5.6	3.0	65.0	.6	1.8	.26	.48	.58	50	25	10
15	21.4	5.4	2.5	66.2	.9	1.9	.44	.23	.59	62	15	10
16	21.8	5.1	2.8	64.7	1.5	1.8	.21	.60	.60	54	22	9
17	----	-----	-----	----	----	----	.33	.43	.61	----	----	----
18	20.9	6.4	1.9	63.6	3.0	2.2	.25	.56	.62	48	24	14
19	22.6	5.5	3.0	64.0	.8	1.9	.17	.70	.63	42	33	10
20	----	-----	-----	----	----	----	.35	.43	.63	----	----	----
21	----	-----	-----	----	----	----	.36	.44	.65	----	----	----
22	20.5	6.1	3.2	64.6	1.1	2.2	.45	.34	.67	55	17	11
23	----	-----	-----	----	----	----	.31	.54	.67	----	----	----
24	----	-----	-----	----	----	----	.27	.62	.68	----	----	----
25	21.4	5.0	3.6	63.4	2.8	1.6	.62	.10	.69	52	22	7
26	----	-----	-----	----	----	----	.32	.60	.71	----	----	----
27	21.1	4.4	4.0	63.4	3.1	1.7	.23	.74	.72	58	17	5
28	----	-----	-----	----	----	----	.34	.61	.74	----	----	----
29	20.9	6.2	3.2	63.1	1.8	1.8	.15	.67	.77	47	25	11
30	22.2	5.4	2.6	62.5	3.3	1.8	.29	.77	.80	41	33	10
31	20.1	6.6	2.8	63.4	2.9	1.7	.40	.61	.80	52	18	13
32	21.7	4.9	3.1	63.6	2.3	1.8	.14	1.04	.82	51	24	8
33	----	-----	-----	----	----	----	.34	.76	.84	----	----	----
34	----	-----	-----	----	----	----	.34	.90	.93	----	----	----
35	21.4	5.3	2.6	64.9	1.4	1.5	.95	.06	.99	58	18	10
36	22.6	6.2	1.8	62.1	1.7	2.2	.73	.39	.99	30	42	14

all cements, even with as little as 0.22 percent alkali, may furnish mortar which will expand excessively if sand with a critical amount of alkali–reactive substance is used.

All of the eight cements in the group which had less than 0.40 percent alkali (cements 1–8) gave more expansion when used with sand containing 1 percent opal than when used with sand containing larger amounts of the reactive mineral. Twenty-five of the twenty-eight cements having more than 0.40 percent alkali (cements 9–36) gave as much, or more, expansion with sand containing 2 percent opal as with sand containing 1 percent and all showed more expansion with 2 percent opal than with 5 percent.

The relation between the alkali content of the cement and the expansion of mortar at ages of 1 and 18 months is shown in figure 4. Mortar prepared with sand containing 1 percent opal developed maximum expansion at 18 months with cement containing 0.6 to 0.7 percent alkali. With greater amounts of alkali, a regression of the expansion of the mortar was found.

When sand with 2 percent opal was used, maximum expansion of mortar at 18 months was obtained with cement containing about 0.9 percent alkali. The data shown for mortar prepared with sand having 5 percent opal indicate that for this condition the maximum expansion of mortar at 18 months may be obtained with cement having considerably more alkali than any cement used in these tests. It seems probable that this curve would flatten out as do those for 1 and 2 percent opal.

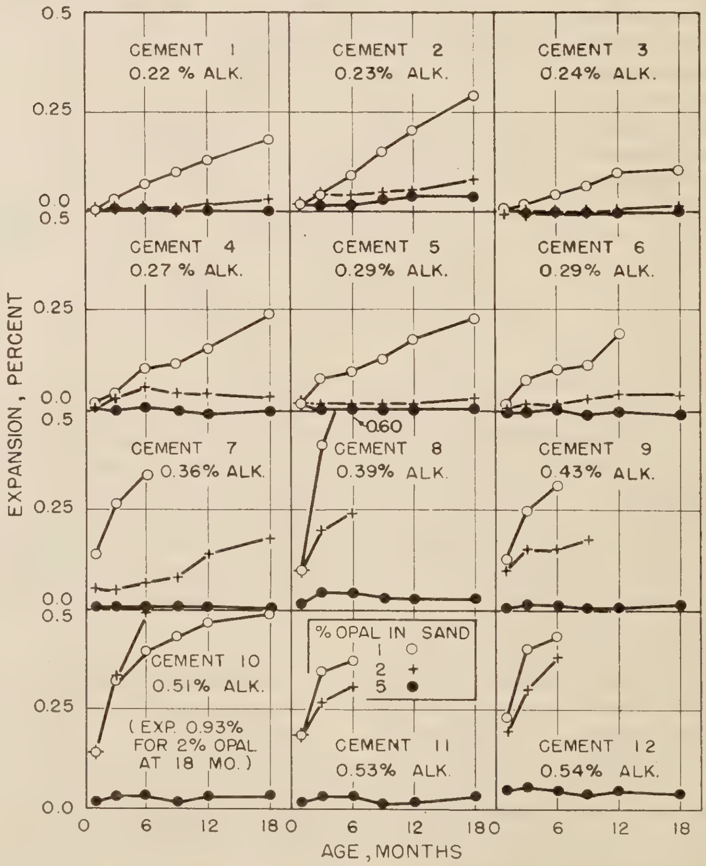

Figure 3A.—Expansion of 1:2 mortar prepared with cements having various percentages of alkali content and sand containing 1, 2, and 5 percent opal.

Expansion at Eighteen Months

The average curves shown separately for 1, 2, and 5 percent opal are replotted in the summary chart in figure 4 for the purpose of ready comparison. As both sets of curves in this chart show similar trends and as the tests at 18 months may be considered to represent more closely the ultimate behavior of these mortars, reference to the curves for the tests at 18 months will be made. Possibly the most important feature shown is that when used with cement of low-alkali content, 0.4 percent or less, sand containing a small amount of opal will produce mortar having an excessive amount of expansion (over 0.1 percent) while sand with a greater opal content may furnish mortar having but little expansion. When cements with less than about 0.4 percent alkali were used, mortars prepared with sand containing 1 percent opal had greater expansion than those prepared with the other two sands. The curve for mortar prepared with sand containing 2 percent opal shows low amounts of expansion for cements with an alkali content of 0.3 percent or less, and that for sand with 5 percent opal shows expansions of less than 0.1 percent for cements containing about 0.6 percent alkali or less.

Sand containing 1 percent opal furnished mortar with a greater amount of expansion than sand containing 5 percent opal when used with cement containing about 0.9 percent

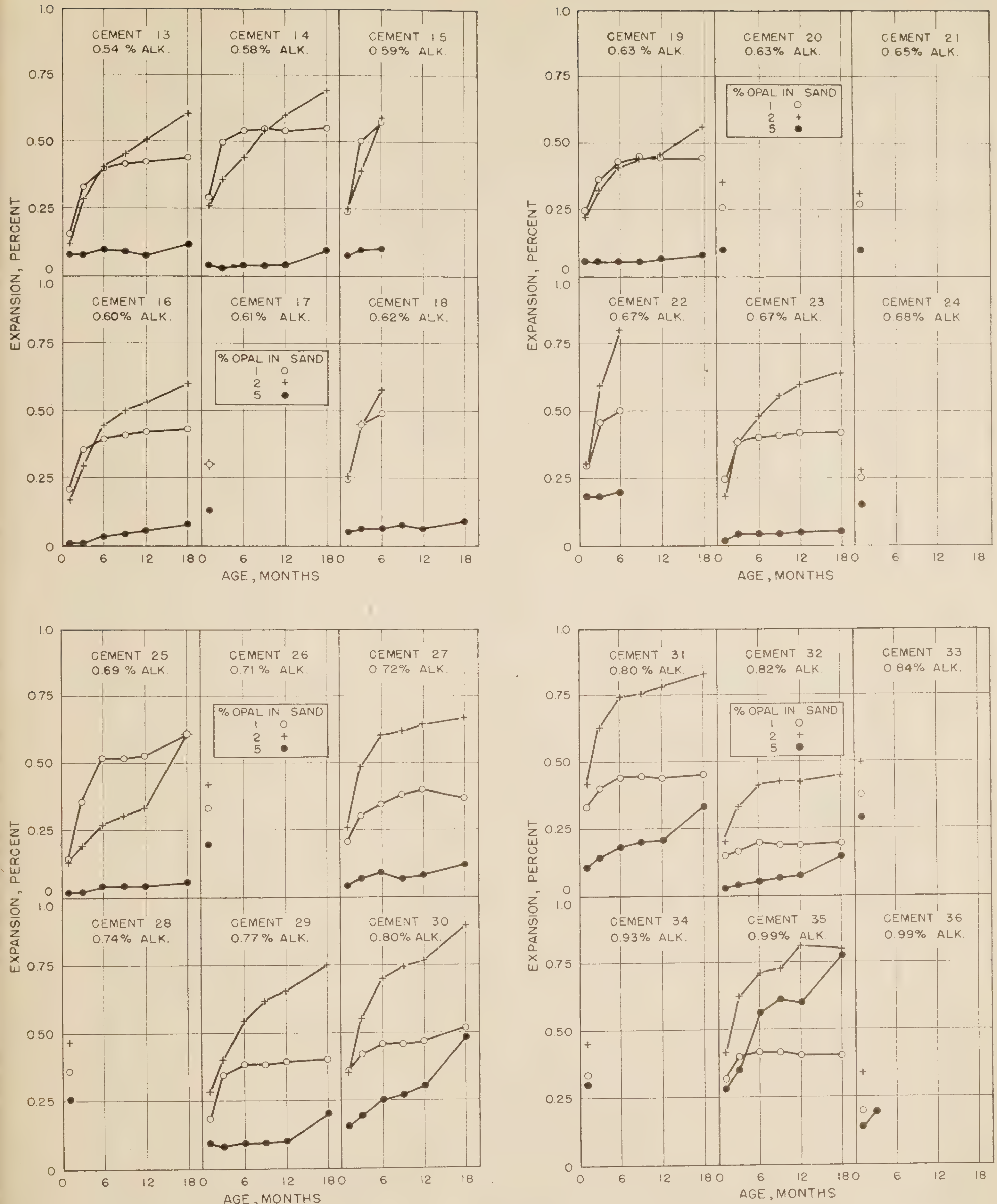

Figure 3B.—Expansion of 1: 2 mortar prepared with cements having various percentages of alkali content and sand containing 1, 2, and 5 percent opal—Continued.

Table 2.—Expansion of 1:2 mortar prepared with Ottawa sand containing different amounts of opal (moist air storage at 100° F.)

Cement number	Alkali content of cement	Opal content of sand	Number of specimens tested	Expansion at age of— 1 month	3 months	6 months	9 months	12 months	18 months
	Percent	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	0.22	1	6	0.00	0.03	0.07	0.10	0.13	0.18
		2	6	.00	.01	.01	.01	.02	.03
		5	6	.00	.01	.01	.00	.00	.00
2	.23	1	2	.02	.04	.09	.16	.21	.29
		2	2	.02	.04	.04	.05	.06	.08
		5	2	.02	.02	.02	.03	.04	.04
3	.24	1	6	.01	.02	.04	.07	.10	.11
		2	6	.00	.01	.00	.00	.01	.02
		5	6	.00	.00	.00	.00	.00	.00
4	.27	1	4	.02	.04	.11	.12	.16	.24
		2	4	.01	.03	.05	.01	.04	.03
		5	6	.01	.00	.01	.00	−.01	.00
5	.29	1	8	.02	.08	.10	.13	.18	.23
		2	8	.02	.02	.02	.02	.02	.03
		5	8	.02	.01	.01	.01	.01	.01
6	.29	1	4	.02	.08	.11	.12	.19	------
		2	6	.01	.02	.02	.03	.04	.04
		5	6	.00	.00	.01	−.01	.00	−.01
7	.36	1	6	.14	.27	.34	------	------	------
		2	6	.05	.05	.07	.08	.14	.18
		5	6	.01	.01	.01	.01	.01	.00
8	.39	1	8	.10	.42	.60	------	------	------
		2	8	.10	.20	.24	------	------	------
		5	8	.02	.04	.04	.03	.03	.03
9	.43	1	6	.13	.25	.32	------	------	------
		2	4	.10	.16	.16	.18	------	------
		5	6	.01	.02	.02	.01	.01	.02
10	.51	1	2	.14	.32	.39	.43	.47	.49
		2	2	.14	.33	.49	.66	.77	.93
		5	2	.02	.03	.03	.02	.03	.03
11	.53	1	4	.18	.34	.37	------	------	------
		2	4	.18	.27	.31	------	------	------
		5	6	.02	.03	.03	.02	.02	.03
12	.54	1	4	.23	.40	.43	------	------	------
		2	4	.19	.30	.38	------	------	------
		5	6	.05	.06	.05	.04	.05	.04
13	.54	1	2	.16	.33	.40	.42	.43	.44
		2	2	.12	.28	.41	.46	.51	.61
		5	2	.08	.08	.10	.09	.08	.12
14	.58	1	2	.29	.50	.54	.55	.54	.56
		2	2	.26	.36	.44	.54	.60	.69
		5	2	.04	.03	.04	.04	.04	.10
15	.59	1	6	.24	.51	.58	------	------	------
		2	6	.25	.39	.59	------	------	------
		5	6	.08	.10	.11	------	------	------
16	.60	1	10	.21	.35	.39	.41	.42	.43
		2	10	.17	.29	.44	.50	.53	.60
		5	10	.01	.01	.03	.04	.06	.08
17	.61	1	6	.30	------	------	------	------	------
		2	6	.30	------	------	------	------	------
		5	6	.13	------	------	------	------	------
18	.62	1	6	.25	.45	.49	------	------	------
		2	6	.26	.45	.58	------	------	------
		5	6	.06	.07	.07	.08	.07	.09

Cement number	Alkali content of cement	Opal content of sand	Number of specimens tested	Expansion at age of— 1 month	3 months	6 months	9 months	12 months	18 months
	Percent	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
19	0.63	1	2	0.24	0.36	0.43	0.45	0.44	0.44
		2	2	.22	.32	.41	.44	.46	.56
		5	2	.06	.06	.06	.06	.07	.08
20	.63	1	6	.26	------	------	------	------	------
		2	6	.35	------	------	------	------	------
		5	6	.10	------	------	------	------	------
21	.65	1	6	.27	------	------	------	------	------
		2	6	.31	------	------	------	------	------
		5	6	.10	------	------	------	------	------
22	.67	1	4	.29	.46	.50	------	------	------
		2	4	.30	.59	.80	------	------	------
		5	4	.18	.18	.19	------	------	------
23	.67	1	2	.24	.38	.40	.41	.42	.42
		2	2	.18	.38	.48	.56	.60	.64
		5	2	.02	.04	.04	.04	.05	.06
24	.68	1	6	.25	------	------	------	------	------
		2	6	.28	------	------	------	------	------
		5	6	.15	------	------	------	------	------
25	.69	1	2	.14	.36	.52	.52	.53	.61
		2	2	.13	.19	.27	.30	.33	.61
		5	2	.02	.02	.04	.04	.04	.06
26	.71	1	6	.33	------	------	------	------	------
		2	6	.42	------	------	------	------	------
		5	6	.19	------	------	------	------	------
27	.72	1	2	.21	.30	.34	.38	.40	.37
		2	2	.26	.48	.60	.62	.64	.67
		5	2	.04	.07	.09	.07	.08	.12
28	.74	1	8	.36	------	------	------	------	------
		2	8	.47	------	------	------	------	------
		5	8	.26	------	------	------	------	------
29	.77	1	2	.18	.34	.38	.38	.39	.40
		2	2	.28	.40	.54	.62	.66	.75
		5	2	.09	.08	.09	.09	.10	.20
30	.80	1	10	.36	.42	.46	.46	.47	.52
		2	10	.35	.55	.70	.74	.77	.90
		5	10	.16	.19	.25	.27	.30	.48
31	.80	1	10	.33	.40	.44	.45	.44	.46
		2	10	.42	.63	.74	.76	.78	.83
		5	10	.11	.14	.18	.20	.21	.33
32	.82	1	10	.15	.17	.20	.19	.19	.20
		2	10	.21	.33	.42	.43	.43	.46
		5	10	.03	.04	.06	.07	.08	.15
33	.84	1	6	.38	------	------	------	------	------
		2	6	.50	------	------	------	------	------
		5	6	.29	------	------	------	------	------
34	.93	1	6	.33	------	------	------	------	------
		2	6	.45	------	------	------	------	------
		5	6	.30	------	------	------	------	------
35	.99	1	10	.32	.40	.42	.42	.41	.41
		2	10	.42	.63	.72	.73	.82	.81
		5	10	.28	.35	.57	.62	.61	78
36	.99	1	2	.20	------	------	------	------	------
		2	2	.34	------	------	------	------	------
		5	2	.14	.20	------	------	------	------

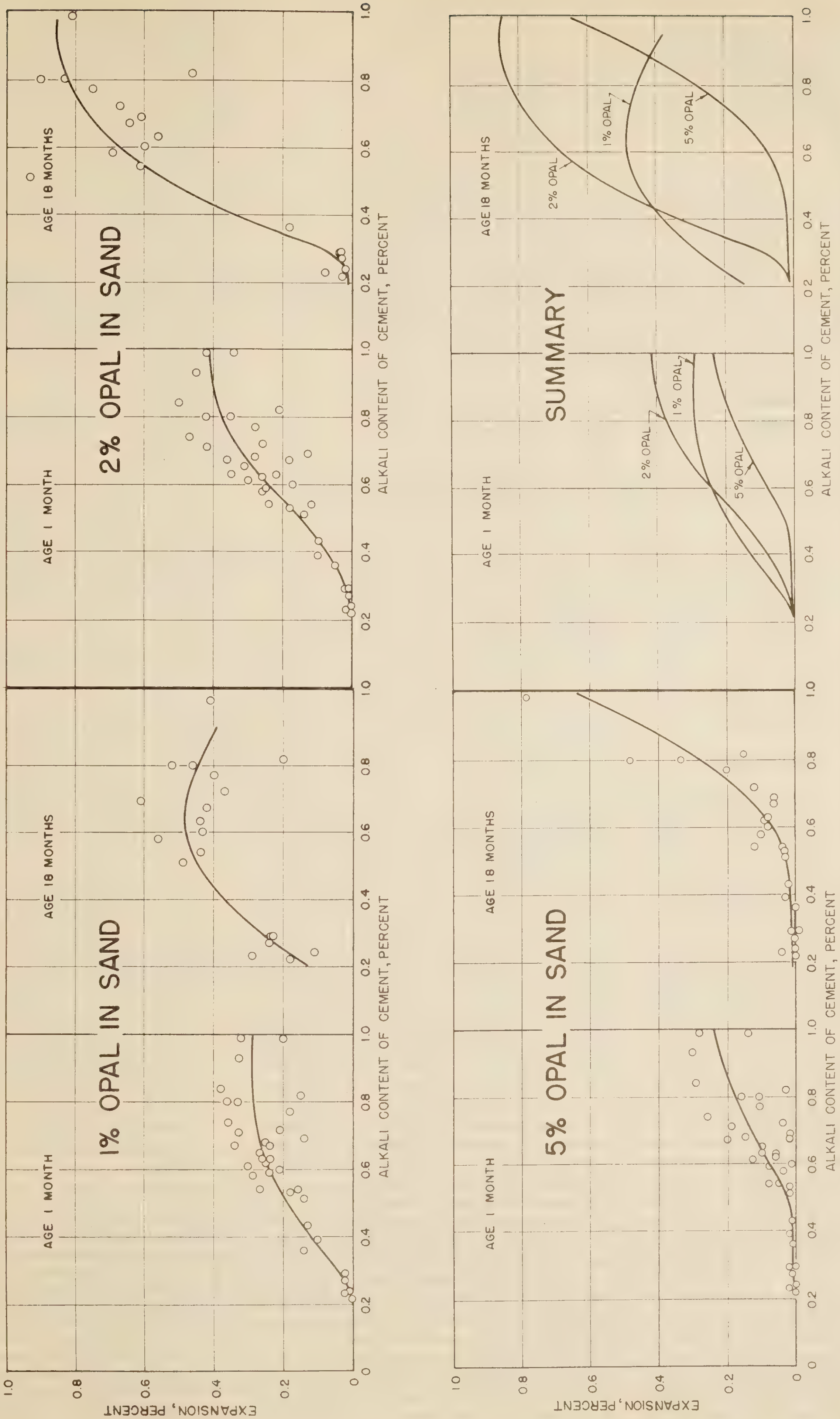

Figure 4.—Relation between alkali content of cement and expansion of 1: 2 mortar prepared with sand containing 1, 2, and 5 percent opal.

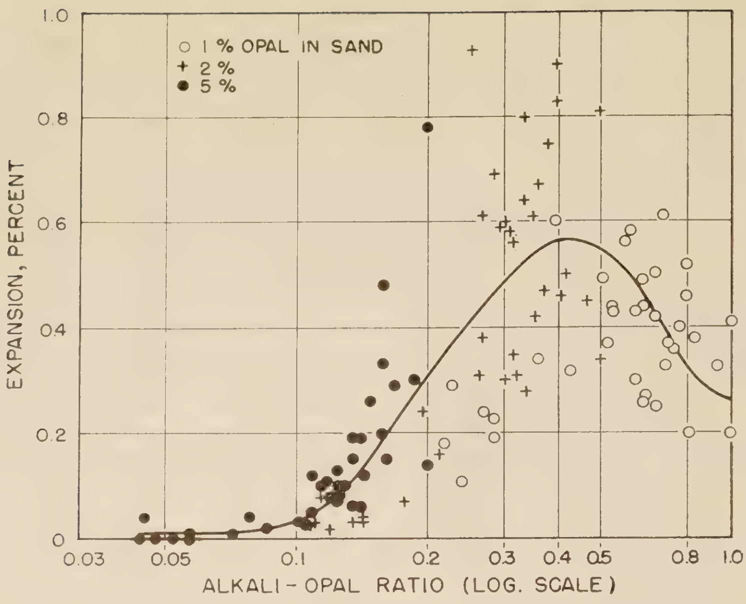

Figure 5.—Relation between alkali–opal ratio and expansion of 1 : 2 mortar prepared with sand containing 1, 2, and 5 percent opal.

alkali or less, and sand containing 2 percent opal furnished mortar which expanded more than that prepared with 5 percent opal for all cements included in these tests. The trend of the curves indicates that for cements containing about 1.1 percent alkali or more, mortar prepared with sand containing 5 percent opal would have greater expansion than that prepared with sand containing 2 percent opal.

Alkali–Opal Ratio Important

From the above it appears that, for mortar of maximum expansion, the alkali content of the cement must increase as the opal content of the sand increases within the range of chemical content of the materials used in these tests. This suggests that a ratio of alkali content to opal content might be used to indicate for mortar of given proportions the combination of cement and aggregate which will furnish the most undesirable characteristics to the mortar, and also the combinations which will produce mortar having relatively a small amount of expansion. The use of such a ratio is shown in figure 5.

In this figure, the values plotted are those for each of the three mortars prepared with a given cement at the greatest age shown in table 2 common for all three mortars. Some of these values were determined at an age of 1 month, others at ages of 6, 12, and 18 months. Although the values plotted have considerable dispersion, they serve to illustrate the development of maximum expansion for a particular combination of cement and reactive sand and not necessarily for cement of the maximum alkali content.

With the materials used in these tests, the maximum amount of expansion of mortar was obtained when the alkali–opal ratio was approximately 0.4. This is, of course, an average value representing the three reactive sands used in these tests. Low amounts of expansion, that is expansions of less than the 0.1 percent cited by the proposed A.S.T.M. specification C 33, were obtained with combinations of cement and aggregate having an alkali–opal ratio of 0.13 or less. Thus it appears that highly reactive aggregates and cements containing high amounts of alkali may furnish mortar or concrete with less expansion than aggregates containing small amounts of reactive material and low- or moderate-alkali cements.

Maximum Expansion Considered

Frequent mention has been made here of the maximum expansion of mortar or concrete. In consideration of the expansion of materials due to the alkali-aggregate reaction, the development of an objectionable amount of expansion, which may be much smaller than the maximum amount, must not be ignored. However, in comparisons between different materials, the maximum expansion obtained may be that considered in the selection of a material or a combination of materials for use. In this discussion, consideration of the maximum expansion found is believed permissible provided attention is directed to the desirability of establishing, when needed, limiting values for the expansion.

It is probable that the alkali-reactive aggregate ratio for maximum expansion of mortar or concrete will vary depending on the characteristics of the reactive aggregate used. If the reactive aggregate is wholly opal, the ratio for maximum expansion may be close to that determined here. If the reactive aggregate is semi-opal, or volcanic glass, or any of other alkali-soluble forms of silica, the ratio which will give the most undesirable properties to the cement product may be quite different from that mentioned here.

Many additional tests would be required to develop this relation fully, and at present there seems to be little need for this complete determination. The number of cements included in these tests and the uniformity o[f] the results obtained appear to be sufficien[t] to warrant the statement that, for the maximum expansion of a mortar of given proportions, the controlling factor is the alkali-reactive aggregate ratio and not the tota[l] alkali in the cement.

Particular attention was given to the magnesia content of each cement, as it has bee[n] stated that magnesia joins with the alkali i[n] promoting reaction with the aggregate. Onl[y] five of the cements for which complete analyses are shown have 3.0 percent or mor[e] magnesia, and none exceed the specificatio[n] limit of 5.0 percent. Only one of thes[e] cements (cement 2) produced mortar with [a] significantly greater amount of expansion tha[n] that shown by mortars prepared with cement[s] of about the same alkali content but wit[h] appreciably less magnesia. No well-define[d] relation between any of the determination[s] of the oxides, other than the alkali, and th[e] expansion of mortar can be found in thes[e] data.

Similar Results Found by Others

Subsequent to the development of the conclusions reported here, attention was draw[n] to work along similar lines by C. E. S. Davi[s] of the Commonwealth Scientific and Industrial Research Organization of Australia. Tests were made of mortar prepared wit[h] inert sand containing 2.5, 5.0, and 10.0 percen[t] opal and cements having from 0.03 to 1.9[?] percent sodium oxide. The cements wer[e] prepared in the laboratory. In a summar[y] of the results of these tests, the followin[g] statements were made:

> The rate and amount of expansion depended also on the opal content of aggregate and on the opal to soda ratio. The most striking illustration of this was that low-soda clinkers (containing 0.35–0.49 percent Na_2O), which did not cause significant expansion with aggregates containing 5 percent opaline rock, eventually expanded mortar made with aggregates containing 2.5 percent of opaline rock. It may thus be inferred that clinkers of even lower soda content may cause expansion if made into mortar with aggregates containing 2.5 percent or less of opaline rock.
>
> As the soda content of clinker increased, the amount of opal required for maximum expansion (Stanton's "pessimum proportion") also increased.

Although he did not develop the informatio[n] as fully as might be desirable, Davis' referenc[e] to the opal to soda ratio and his inferenc[e] regarding the behavior of cements of ver[y] low-alkali content agree substantially wit[h] the findings of this investigation.

(*Continued on page 49.*)

[4] *The effect of soda content and of cooling rate of portlan[d] cement clinker on its reactions with opal in mortar*, by C. E. S[.] Davis. Australian Journal of Applied Science, vol. 2, No. 1[,] March 1951.

U. S. GOVERNMENT PRINTING OFFICE: 1952

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Bibliography on Automobile Parking in the United States.
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Express Highways in the United States: a Bibliography.
Indexes to PUBLIC ROADS, volumes 17–19, 22, and 23.
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STATUS OF FEDERAL-AID HIGHWAY PROGRAM

AS OF JUNE 30, 1952

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM											
		PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$6,031	$35,523	$17,882	553.3	$8,819	$4,828	192.2	$21,750	$10,764	428.5	$66,092	$33,474	1,174.0
Arizona	822	4,120	2,748	107.5	1,002	524	20.3	9,719	6,562	128.2	14,841	9,834	256.0
Arkansas	3,172	10,278	5,461	285.9	7,575	3,752	213.8	17,135	8,704	494.7	34,988	17,917	994.4
California	3,197	20,846	6,271	147.7	19,355	9,451	72.9	86,968	42,264	252.7	127,169	57,986	473.3
Colorado	4,643	5,240	2,924	116.7	2,547	1,397	64.4	13,988	7,125	280.8	21,775	11,446	461.9
Connecticut	6,425	2,104	1,102	5.8	2,161	1,055	9.0	10,546	5,579	16.4	14,811	7,736	31.2
Delaware	2,317	335	165	1.7	2,023	1,011	8.0	6,063	2,670	49.9	8,421	3,846	59.6
Florida	3,050	17,854	9,187	305.2	7,792	3,976	129.5	14,988	7,599	270.8	40,634	20,762	705.5
Georgia	3,630	19,168	9,898	487.2	9,605	4,805	111.2	34,694	16,500	582.1	63,467	31,203	1,180.5
Idaho	5,416	8,220	5,122	228.5	3,385	2,181	45.3	6,672	4,299	160.2	18,277	11,602	434.0
Illinois	10,794	51,148	28,253	461.0	17,988	9,017	205.8	82,454	41,575	715.7	151,590	78,845	1,382.5
Indiana	7,347	40,169	20,343	259.4	7,764	4,445	162.0	28,861	15,345	333.7	76,794	40,133	755.1
Iowa	1,932	12,870	6,868	358.8	10,677	5,429	448.3	19,841	9,874	885.5	43,388	22,171	1,692.6
Kansas	7,179	10,784	5,239	1,017.4	5,349	2,691	524.8	16,670	8,691	563.1	32,803	16,621	2,105.3
Kentucky	1,571	21,157	11,257	416.0	7,120	3,483	135.0	16,513	8,583	327.3	44,790	23,323	878.3
Louisiana	3,031	15,455	7,381	114.4	10,933	4,986	31.5	20,621	10,289	216.5	47,009	22,656	362.4
Maine	823	10,764	5,622	100.3	1,111	677	7.5	9,705	4,878	74.5	21,580	11,177	182.3
Maryland	4,956	9,919	4,558	71.4	1,700	851	68.4	10,186	5,468	19.1	21,805	10,877	158.9
Massachusetts	3,855	4,861	2,559	18.1	9,444	4,486	8.4	47,965	23,570	47.4	62,270	30,615	73.9
Michigan	2,958	29,833	15,046	490.8	11,719	5,858	240.8	59,152	26,036	350.9	100,704	46,940	1,082.5
Minnesota	3,749	9,612	5,144	1,126.5	9,340	4,674	723.0	27,828	15,113	999.2	46,780	24,931	2,848.7
Mississippi	4,063	17,330	8,921	559.7	5,884	2,906	188.0	16,499	8,628	468.4	39,713	20,457	1,216.1
Missouri	9,370	27,714	14,084	896.5	15,011	7,505	252.9	40,845	21,422	659.5	83,570	43,011	1,808.9
Montana	8,709	9,307	5,519	292.7	4,669	2,721	71.1	20,719	12,475	352.2	34,695	20,715	716.0
Nebraska	11,196	12,027	6,311	583.1	5,937	2,948	156.0	18,826	9,334	601.6	36,790	18,593	1,340.7
Nevada	2,519	7,338	5,831	250.7	175	146	35.9	5,653	4,704	222.4	13,166	10,681	509.0
New Hampshire	1,592	5,416	2,847	28.7	615	311	5.2	6,898	3,438	46.9	12,929	6,596	80.8
New Jersey	1,645	10,336	5,086	46.1	8,506	4,254	14.4	30,967	15,316	25.4	49,809	24,656	85.9
New Mexico	1,371	4,616	2,954	150.9	2,827	1,788	104.9	13,240	8,458	306.6	20,683	13,200	562.4
New York	24,122	96,297	50,015	205.2	31,993	14,989	177.9	107,540	49,118	399.4	235,830	114,122	782.5
North Carolina	4,403	24,580	11,967	437.7	5,928	2,831	142.7	23,715	11,620	464.9	54,223	26,418	1,045.3
North Dakota	1,551	7,786	4,025	1,116.8	8,679	4,431	783.5	9,901	4,971	796.4	26,366	13,427	2,696.7
Ohio	8,930	36,801	18,229	127.0	16,591	8,524	58.4	76,994	38,903	246.3	130,386	65,656	431.7
Oklahoma	2,659	15,944	8,822	224.9	7,398	3,884	169.3	23,449	12,407	263.4	46,791	25,113	657.6
Oregon	1,708	2,418	1,429	27.1	3,327	1,961	85.1	17,957	10,242	238.9	23,702	13,632	351.1
Pennsylvania	5,765	38,222	19,103	122.5	24,397	12,160	43.7	73,733	36,609	198.9	136,352	67,872	365.1
Rhode Island	771	4,355	2,178	35.0	2,380	1,190	8.2	17,212	8,984	24.9	23,947	12,352	68.1
South Carolina	3,516	10,400	5,643	327.3	3,915	1,945	217.4	15,867	8,126	362.3	30,182	15,714	907.0
South Dakota	1,205	7,704	4,441	662.0	4,186	2,440	246.6	13,897	8,046	774.1	25,787	14,927	1,682.7
Tennessee	3,745	12,178	5,803	408.3	13,581	6,501	351.2	30,336	14,437	444.2	56,095	26,741	1,203.7
Texas	12,184	6,832	3,387	163.1	16,572	9,400	461.2	59,219	30,666	1,071.8	82,623	43,453	1,696.1
Utah	1,344	5,050	3,859	160.6	1,900	1,526	10.2	8,451	6,237	152.9	15,401	11,622	323.7
Vermont	1,132	4,903	2,636	46.1	623	321	8.6	6,870	3,441	56.5	12,396	6,398	111.2
Virginia	4,996	20,424	10,195	326.5	6,781	3,399	131.3	25,390	12,723	386.8	52,595	26,317	844.6
Washington	2,315	12,343	5,920	166.1	3,017	1,581	88.2	18,166	9,106	174.9	33,526	16,607	429.2
West Virginia	2,920	12,957	6,539	104.5	4,494	2,271	48.5	14,195	7,075	135.3	31,646	15,885	288.3
Wisconsin	4,198	22,637	12,014	436.5	9,757	4,445	223.8	31,276	15,893	474.4	63,670	32,352	1,134.7
Wyoming	266	3,224	2,109	99.0	1,656	1,098	63.7	9,306	6,137	159.8	14,186	9,344	322.5
Hawaii	1,542	5,047	2,371	8.3	2,495	1,235	10.7	11,092	4,489	21.3	18,634	8,095	40.3
District of Columbia	618	13,459	5,909	1.4	2,654	1,324	.5	3,028	1,707		19,141	8,940	1.9
Puerto Rico	5,145	6,467	3,068	39.2	3,842	1,845	18.7	10,754	5,080	31.2	21,063	9,993	89.1
TOTAL	222,398	804,372	414,245	14,727.1	377,199	191,459	7,599.9	1,324,314	671,280	16,758.8	2,505,885	1,276,984	39,085.8