also often called nuclear-electric drives because, for most of them, the approach is that of converting fission energy to electricity and using the electricity to accelerate charged particles to produce thrust. Invariably the power plants are heavy, the thrust is low, and the resulting vehicle accelerations are very low—less than 0.001*g*. Since the vehicle acceleration is low, the engine operating time has to be long (measurable in months for most missions) if a reasonable velocity and trip time are to be achieved. In order for such a propulsion engine to be attractive, the power in the exhaust jet per kilogram of engine weight should be as high as possible. A specific jet power of 0.05 kilowatt per kilogram will probably be useful, but 0.15 kilowatt per kilogram would be very much better. A lot of effort has been devoted, with a good deal of success, to developing thrust mechanisms such as ion accelerators and plasma accelerators, but the real crux of the problem is the power plant. There are numerous ways to convert heat energy into electrical energy, of which perhaps the most familiar are those based on use of thermodynamic cycles and rotating machinery. Another attractive approach is the direct conversion of fission heat into electricity by means of thermionic cells. The first demonstration in a nuclear reactor of such a device was made at Los Alamos as long ago as 1959. The development of a complete nuclear-electric propulsion system will be difficult and expensive, but if man wants to continue to explore space to the best of his ability, such a development seems inevitable.

References and Notes

1. Early (1946) secret reports were issued by North American Aviation, Inc., and by Douglas Aircraft Company (Project Rand). An unclassified report was issued in January 1947 by the Applied Physics Laboratory, Johns Hopkins University. The most readily accessible early work is that of A. V. Cleaver and L. R. Shepherd published in the September and November 1948 and the January and March 1949 issues of the *Journal of the British Interplanetary Society*. These articles were later incorporated into the book *Realities of Space Travel*, L. J. Carter, Ed. (Putnam, London, 1957).
2. R. W. Bussard and R. D. DeLauer, *Nuclear Rocket Propulsion* (McGraw-Hill, New York, 1958). A good account of nuclear rockets is to be found in *Nuclear Propulsion for Space* by W. R. Corliss. This booklet is one of a series on *Understanding the Atom*, published by the Division of Technical Information of the U.S. Atomic Energy Commission. Copies may be obtained by writing to USAEC, P.O. Box 62, Oak Ridge, Tenn. 37830.
3. P. G. Johnson, *Astronaut. Aeron.* **2**, 22 (Dec. 1964); A. R. Chovit, C. D. Kylstra, R. K. Plebuch, *ibid.* **3**, 36 (June 1965). The June 1965 issue contains several articles on nuclear rockets.
4. I am indebted to the Westinghouse Astronuclear Laboratory for Fig. 4.

Friction of Rubber on Wet Surfaces

Knowledge of the mechanism of friction is important for progress in traffic safety.

E. M. Bevilacqua and E. P. Percarpio

In this article we describe recent progress in understanding friction of rubber on wet surfaces (lubricated friction of rubber) (*1*). When reading titles of articles in journals like *Physical Review Letters,* one sometimes wonders how many physicists riding to work with their heads in the cosmos among quasars and quarks realize that an important unsolved problem of physics travels with them. The control of friction is important in many aspects of life, including, most importantly, riding to work, for the interface between tires and roads is the only connection between vehicle and environment. A quick review of indexes of *Science* for the last two decades reveals only two entries under the heading "Friction." The first (*2*) deals with a simple laboratory device for an elementary mechanics experiment, a kind of experiment from which most scientists of the present generation probably learned most of what they know about friction. The second (*3*) is a book review in which the introductory paragraphs point out the wide range and importance of problems involving friction. Within these two decades there has been a substantial increase in research interest in such problems and, in the area covered by this review, substantial progress.

Lubricated Friction Mechanism

The importance of lubricated friction of rubber has become increasingly obvious in the past decade as driving speeds have increased. As a result, those who begin research on the subject soon drive more slowly when roads are wet, for high friction at the interface between tire and wet road is desired—a respect in which this problem differs from most others involving friction. This is an apparently uncomplicated problem; friction of rubber on wet surfaces, under the most important practical conditions, is determined entirely by energy losses in the rubber that are produced by its deformation by the hard surface over which it slides. The principal research problem is, then, to define how this hysteretic loss is evoked by the hard surface during sliding. It now turns out that knowledge of this mechanism is essential for the practical problems of designing tires and roads.

Because of the way in which friction arises when rubber slides over a hard surface, the structure of that surface determines the absolute friction level. This can be illustrated conveniently by the data of Table 1, assembled from several different experiments.

The data of row 1 in Table 1 show the friction of a standard specimen of rubber on a typical slippery road surface in the absence of ice. When water is substituted for the dilute glycol solution, so that a thin layer of ice is allowed to form, the surface is altered and the friction drops abruptly. Substitution of a piece of smooth wavy glass about as rough as the road causes a slight further drop in friction, showing that the ice did not entirely mask the

The authors are research associate and research engineer, respectively, at the Uniroyal Research Center, Wayne, New Jersey. Dr. Bevilacqua is editor of *Rubber Chemistry and Technology.*

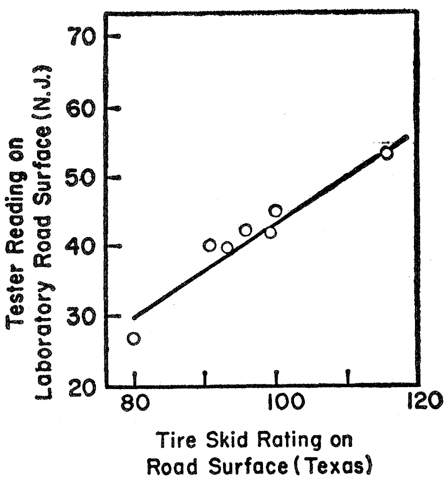

Fig. 1. Comparison of stopping-distance ratings of a series of tires on a slippery road and laboratory measurements, made with the Portable Skid Resistance Tester, for rubber specimens of the same composition as the tires, on a reference surface.

road surface. Finally, the use of ice as smooth and flat as can be easily obtained by remelting a quiescently frozen surface gives a very low coefficient of friction. This dominance of geometrical factors has been responsible for much of the experimental difficulty encountered in studying lubricated friction of rubber. It is perhaps natural to begin research by using flat surfaces. In some of our early work with an apparatus designed by Akkerman (*4*), in which a rubber specimen slides over a plane plate glass, coefficients varied erratically over a two- or threefold range when test pieces of smooth molded rubber were slid on the same piece of plate glass. When the same specimens were abraded only slightly so as to produce uniform roughness, the coefficients all fell within a few percent of each other.

All of our later research has been done with the Portable Skid Resistance Tester, the apparatus used in obtaining the results shown in Table 1, because it gives good correlation with data from large-scale testing of tires on roads. This instrument is based on an apparatus originally designed at the National Bureau of Standards (*5*) for studying rubber heels. We are not familiar with its success for that purpose; in its present form it has proved to be extremely valuable.

Table 1. Friction at temperature of −1.1°C on a series of surfaces.

Surface	"Lubricant"	Friction*
Suburban road	30% Glycol	42.5
Suburban road	Water	13.1
Wavy glass, Syenite†	Water	9.1
Fresh flat ice‡	Water	7.8

* Measured with the standard slider of the Portable Skid Resistance Tester (*6*). Units are approximately 100 times the coefficient of friction (μ) at 275 centimeters per second. † PPG Industries. This glass is about as rough as the road surface. ‡ Freshly melted and refrozen surface of a flat block of ice frozen quiescently.

In order for laboratory results to be applicable to the problem of tires on roads, there need not be a one-to-one correspondence between results in the laboratory and in the field, but only good correlation between the two sets of data. A good correlation between measurements made with the Portable Skid Resistance Tester and data from full-scale tests involving variations in the properties of roads has been established by repeated tests (*6–8*). Figure 1 shows that data obtained with this instrument are also well correlated with data from full-scale tests involving variation of properties of tire-tread materials tested on a slippery road surface (*1*). The responsiveness of the instrument to variations in both road and rubber accounts for its usefulness in the laboratory.

It now appears possible to obtain absolute values for friction coefficients of rubber on hard surfaces, by means of appropriate laboratory measurements on the rubber and the surface. Until very recently this has not been possible (*9*).

Deformation in the Rubber

The only clearly defined source of friction when rubber slides over a hard surface is what we refer to here as deformation. This consists of a nondestructive distortion of rubber at the interface, caused by the combing of large-scale asperities of the hard surface through the rubber. The first suggestion of, and a simple demonstration of, the existence of this mechanism was given by Greenwood and Tabor (*10*). When a series of cones was slid over a well-lubricated rubber surface, the coefficient of friction calculated from the hysteresis of the rubber was very close to the experimental value at mean pressures up to about 450 pounds per square inch (30 bars). At this pressure, corresponding to a cone semiangle of between 45 and 50 degrees, the friction began to rise more rapidly than had been expected from the calculation, and damage to the rubber occurred.

There has been extensive speculative discussion of a second mechanism for friction, referred to as adhesion (*11*), for which there is no direct experimental evidence. We believe that it does not occur in lubricated sliding, and that a third mechanism, which we refer to as abrasive friction, fully accounts for that portion of the sliding friction of rubber on a wet surface which is not contributed by deformation. All of the phenomena observed in the sliding of rubber on road surfaces can be fully accounted for in terms of these two mechanisms (*1*).

Abrasive and deformation contributions to friction are distinguished by the magnitude and characteristic frequency of the distortion of the rubber. Deformation friction results from large-scale distortions *from which the rubber recovers,* involving penetration of the rubber to distances that are approximately the same as the dimensions of the large-scale roughness of the hard surface. Frequencies associated with this are usually low—10^2 to 10^3 hertz, depending on sliding speed and on the dimensions of the asperities. Abrasive friction results from fine-scale roughness which, on the basis of the results of Greenwood and Tabor, can be defined approximately as asperities sharper than a cone of semiangle 45 degrees; this angle may be a function of sliding speed. These asperities penetrate the rubber and, by mechanical interlocking, cause longitudinal distortions at the interface. Because the rubber cannot recover rapidly enough, this distortion is accompanied by abrasion. The frictional energy contributed by tearing is small, most of it coming from the extension and retraction of the surrounding bulk of the material. Distortions are smaller than in deformation friction, and the associated frequencies are correspondingly higher, 10^4 to 10^6 hertz.

An exactly similar mechanism might operate if adhesion between rubber and substrate existed. This may be the case in dry sliding, but such adhesion is of negligible importance in lubricated sliding. The maximum possible contribution of an adhesion term can be estimated from data obtained by Roth and his co-workers (*12*), which indicate that, at low sliding speeds, friction on flat smooth glass lubricated with water is of the order of 4 percent of that on the dry surface. This order of magnitude is in good agreement with our own data. It includes the contribution of the viscosity of the lubricant to friction, as well as the contribution of any adhesion which occurs. In the scale used for the friction measurements of Tables 1 and 2 (*6*), the maximum contribution to friction due to adhesion on the wet surfaces is therefore about 4 units. The demonstration by Greenwood and Tabor (*10*) gives confidence that the actual contribution is zero within the limits of experimental error.

It is possible, with glass as a model substrate, to make a simple laboratory demonstration that two distinct components contribute to lubricated friction. In Fig. 2 the two specimens in the upper row are commercially available window glass, that on the left (the Syenite of Table 1) having an undulating pattern, that on the right being plane. The two specimens in the lower row are of the same kinds of glass, respectively, as the corresponding specimens in the top row, but those in the bottom row had been subjected to erosion by sandblasting simultaneously in the same chamber—a treatment which added the same fine-scale roughness to both surfaces. If this kind of roughness contributes to friction independently of the larger-scale wavy roughness, then measurements of friction on the plane sandblasted glass (bottom right) and on the rippled glass (top left) should add linearly to give a prediction of friction on the glass specimen having both large- and fine-scale texture (bottom left). Measurements on the flat glass surface (top right) provide an estimate of the total of other contributions to friction (*1*). Table 2 shows that the expectation of simple additivity was borne out, within the limits of experimental error. The specimens of rubber listed in Table 2 (butyl, EPT, SBR blend, and natural) were chosen to give a very wide range of the properties that are important in determining friction: modulus and hysteresis. Details of these contributions are discussed below; here we need only note certain important effects of the differences in surface texture of the hard substrates on the coefficient of friction. The values in row 1 show that, with a flat surface, coefficients of friction are uniformly low, and that the differences in values for different rubber specimens are almost within the limits of experimental error. With the wavy glass (row 2) the coefficient of friction increases substantially, and there are much larger differences in the values for the various rubbers, reflecting their bulk hysteresis. With the flat sandblasted glass (row 3) the total friction increases still more, the differences in values for the different rubber specimens become relatively smaller, and the most hysteretic rubber (butyl) does not have the highest coefficient of friction. As shown in rows 4 and 5 of Table 2, arithmetical calculation from the data obtained with the individual surfaces does give a good prediction of the coefficient of friction observed for the composite surface. Reference to the experiment of Greenwood and Tabor cited above (*10*) leads to the conclusion that the contribution of friction on the sandblasted surfaces arises by the same mechanism that is reflected in the data of these workers when damage to the rubber test specimen becomes apparent and the friction begins to rise *faster than is predicted by calculation* from bulk hysteresis losses alone.

Comparison of the results obtained in these simple experiments with model surfaces and results obtained on actual roads suggests that an important measure of the characteristic of roads is the extent to which this kind of friction, which we have called abrasive friction, occurs when rubber slides on the road surface. In measurements on some 160

Table 2. Components of friction.

Row	Surface texture of glass	Skid resistance* at 22.8°C (on water-lubricated surface)			
		Butyl	EPT†	SBR‡ blend	Natural
1	Plane plate	8	4	4	5
2	Syenite, wavy smooth	20	6	12	11
3	Sandblasted plane (minus plane plate)	54	49	61	57
4	(Values calculated for row 5 by adding rows 2 and 3)	74	55	73	68
5	Sandblasted wavy	75	53	68	66

* Measured with the standard slider of the Portable Skid Resistance Tester (*6*). Units are approximately 100 times the coefficient of friction (μ) at 275 centimeters per second. † EPT is an ethylene propylene terpolymer. Royalene 301 was used in this experiment. ‡ SBR is a styrene butadiene copolymer rubber. Synpol 1500 was used in this experiment.

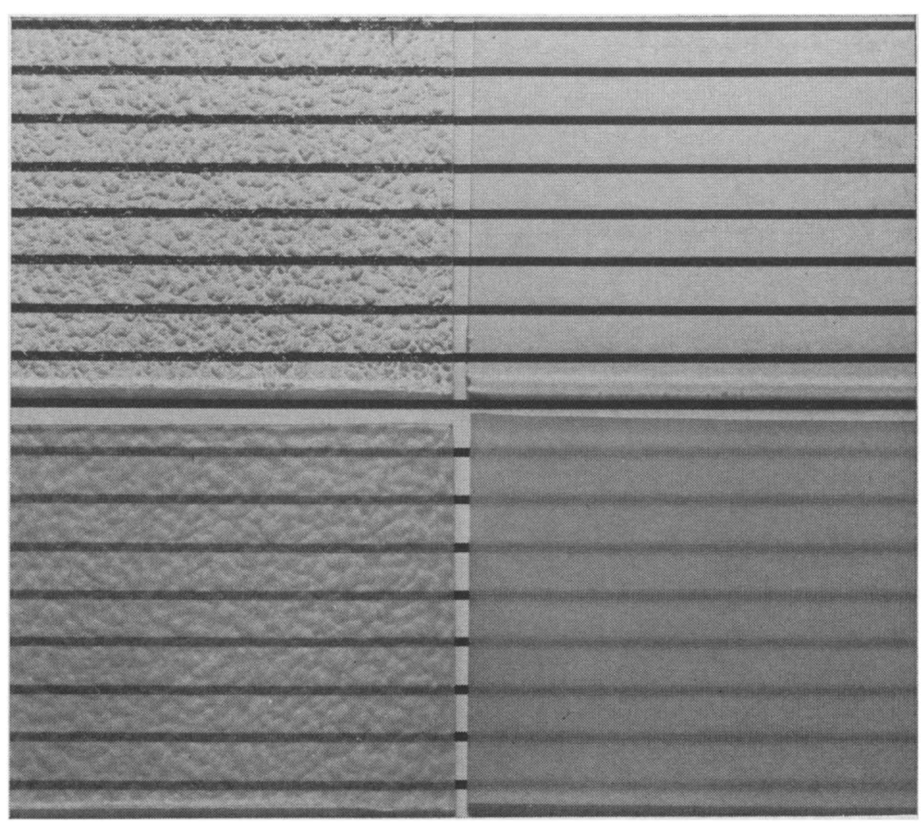

Fig. 2. Glass specimens used to demonstrate additivity of deformation and abrasive components of friction, photographed over a ruled background to accentuate the texture (see text).

Table 3. Regression equations for friction on several surfaces at temperature of 22.8°C.

Surface	Character	Best equation for skid resistance*
Syenite	Wavy	$SR = 26 - 0.22R_{23} - 0.08D$
Slippery road	Composite	$SR = 71 - 0.40R_{0} - 0.18D$
Sandblasted glass	Abrasive	$SR = 60 - 0.40R_{-18} + 0.21D$
Terazzo surface	Abrasive	$SR = 21 - 0.22R_{-18} + 0.21D$

* SR, skid resistance, as shown on the scale of the Portable Skid Resistance Tester; *R*, Bashore rebound (resilience), in percent; *D*, Shore A hardness (modulus). Subscripts on *R* show the temperature of measurment of resilience which gives the best fit in the regression equation for skid resistance at temperature of 22.8°C.

road surfaces, we have never found any surface which, when wet, did not cause abrasive damage to the test specimens, and photomicrographs of the roads always show fine-scale roughness. High friction without abrasive damage can occur on dry surfaces, but not on wet. This distinction between two mechanisms of friction corresponds well with the distinction between sources of abrasion described by Schallamach (*13*).

On the basis of this simple hypothesis that abrasive and deformation components exist in the road surface and that properties of the rubber respond differently to these two types of components, it has been possible to devise a simple analytical technique for studying the properties of roads. In order to identify quantitatively differences between high- and low-friction roads, we have made use of the fact, illustrated in Table 2, that a highly resilient rubber is insensitive to large-scale roughness in the hard surface and a highly hysteretic rubber is sensitive to such roughness. By measuring friction on the entire sample of road surfaces with two test specimens, one highly resilient and one of highly hysteretic rubber, it is possible to estimate the extent to which abrasive friction occurs on each road surface, this being a function of the difference in friction as measured with the two test specimens.

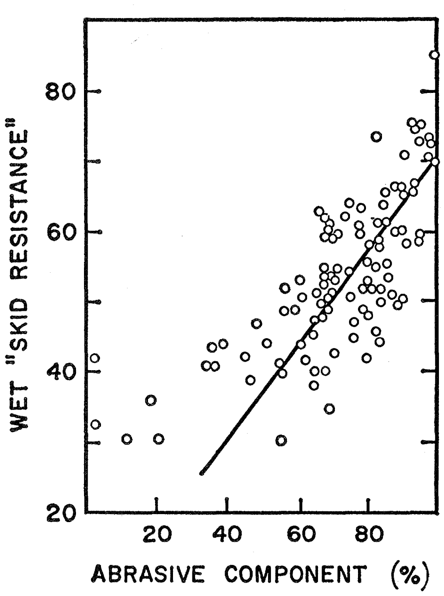

Fig. 3. Relation between slipperiness and abrasive contribution to friction for a sample of 107 road surfaces.

Figure 3 shows that slipperiness is accompanied, for the most part, by a lack of abrasive component in the road surface, a finding in agreement with earlier qualitative observations that slipperiness is caused by the polishing off of fine-scale roughness of the road surface. A comparison of means and distributions of coefficients of friction for roads in many locations in the United States (*1*, *14*), England (*7*), and Germany (*15*) shows paved road surfaces to be quite similar everywhere.

The importance of these data to the design of tires and road surfaces for good traction is made clearer by the discussion of properties of rubber important for wet friction which follows.

Properties of Rubber Important for Friction on Wet Surfaces

Hysteresis is responsible for lubricated friction, but tests with a large number of rubber specimens of different composition show that not only hysteresis but also modulus of elasticity determines the friction coefficient of a rubber specimen on a hard surface.

A linear relation of the form

$$\mu = K + \alpha R + \beta D, \qquad (1)$$

where μ is the coefficient of friction, K is an arbitrary constant, R is resilience [for example, Bashore rebound (*16*)], D is modulus [for example, Shore A hardness (*17*)], and α and β are coefficients characteristic of the road surface, describes the friction of a wide range of rubber specimens of different composition on a wide range of surfaces. The relation of Eq. 1 was determined first for a standard slippery road surface by using a group of 99 rubber specimens for which the properties of hardness and resilience were orthogonal. In further work, a set of 14 compositions was selected from the original large set, by trial and error, to obtain combinations of resilience and hardness representative of all five of the elastomers used in the experiment, while retaining the requisite orthogonality of these properties.

The nature of the parameters in the regression equation (Eq. 1) gives some insight into the friction mechanism. The first obvious point is that the appropriate resilience measurement to use for predicting friction is determined by the fineness of the asperities in the hard surface. For best prediction of friction, resilience should be measured at a characteristic frequency related to the frequency of deformation of the rubber during sliding. This means that with the Bashore rebound instrument (*16*), which we used in our early work (*1*) for measuring resilience, rebound must be measured, for best correlation with the friction measurement, at a temperature lower than that at which the friction on road surfaces is measured. The effective frequency appropriate for measuring friction in sliding that occurs at normal driving speeds is of the order of kilohertz, and that for measuring resilience with the Bashore instrument is less than 100 hertz. In accordance with the well-known W.L.F. transform (*18*), measurement at lower frequency at lower temperature corresponds to a higher frequency at the higher temperature.

Tables 3 and 4 show the way in which the temperature difference (for the two measurements) that gives best correlation depends on the character of the hard surface. The road and the wavy glass plate of Table 3 have about the same large-scale roughness; the frequency associated with friction is apparently determined by the concentration of fine-scale roughness so that, for the glass plate, measurement of rebound at the temperature at which friction is measured gives the best correlation, whereas for the road surface, which has fine-scale roughness, the best correlation is obtained by measuring rebound at a temperature some 20 degrees lower than that at which friction is measured. For the flat ground-glass surface, which has even finer roughness, the temperature difference that gives best correlation is substantially larger.

That this relation is not an artifact of the choice of materials is indicated by the set of data for the road at differ-

Table 4. Regression equations for friction on a road surface as a function of temperature.

Temperature	Best equation for skid resistance*
23	$SR = 60 - 0.40R_0 - 0.12D$
2	$SR = 55 - 0.37R_{-18} - 0.11D$
−1	$SR = 55 - 0.36R_{-18} - 0.11D$
−12	$SR = 56 - 0.35R_{-30} - 0.15D$
−23	$SR = 59 - 0.41R_{-40} - 0.16D$

* SR, skid resistance, as shown on the scale of the Portable Skid Resistance Tester; R, resilience; D, modulus. Subscripts on R show the temperature of measurement of resilience which gives the best fit in the regression equation for skid resistance.

ent temperatures (Table 4). In this case, friction and resilience were measured at a series of temperatures, an antifreeze lubricant being used at the lowest temperatures to prevent the formation of ice, which would change the character of the hard surface. Throughout the series the appropriate temperature for measuring rebound as a basis for predicting friction is approximately 20 degrees lower than the temperature for the friction measurement.

The way in which modulus enters into friction is not entirely clear. It is speculated that the hardness reflects some kind of interaction with the fine-scale abrasive asperities of the surface. However, the contribution made by hardness to friction depends on the large-scale roughness of the surface as well, and it is this fact which establishes the pertinence of friction mechanism to practical design problems.

On a macroscopically flat surface, not only is the lubricated friction low, but differences in friction for different rubber specimens are small. This is illustrated in Table 2 for several rubber specimens on four surfaces. More extensive studies (*1*, *19*) show that the hard surface must have a characteristic peak-to-valley roughness (at least 5×10^{-4} centimeter) in order to produce differences in wet friction with different rubber specimens. Corresponding to this characteristic roughness there is a transition in mechanism, which shows up in the coefficient β, as in Table 3. On superficially flat surfaces or surfaces whose roughness is very fine scale, β is positive. As soon as the large-scale roughness exceeds the critical value, the sign of β changes, becoming negative irrespective of the presence or absence of fine-scale roughness or the size of the wet friction coefficient. This transition remains unexplained at present; its importance lies in the fact that slippery roads have surfaces whose large-scale roughness exceeds the critical value, so that all tests of tires must be made on surfaces for which β is negative.

Application to Movements of Vehicles on Roads

Research on lubricated friction is pertinent to the driving of motor vehicles for two reasons. (i) As mentioned above, accurate knowledge of the mechanism by which friction arises is essential to realistic design and testing of road surfaces and tires. (ii) Friction of tires on wet roads is extremely important to traffic safety.

The importance of friction on wet roads first attracted serious widespread attention in this country about a decade ago. Data presented at the First International Skid Prevention Conference (*20*) showed that, although roads are wet much less of the time than they are dry, the proportion of accidents that involve skidding to accidents that do not is so much higher for wet roads than for dry roads that the actual number of accidents that involve skidding was higher on wet roads. In the ensuing decade average driving speeds in this country have steadily increased, and more recent analyses now show that in some locations, particularly on heavily traveled highways, the number of accidents from all causes on wet roads may exceed the number on dry roads, even though roads are wet only about one-fifth of the time. For example, on Route 52 Bypass in Indiana, accidents from all causes were about six times as frequent on wet pavement as on dry over a 3-year period (*21*), and, on a short stretch on Route 4 in New Jersey, nearly four times as frequent on wet pavement as on dry during 1964. In both instances the number of accidents on wet roads exceeded those on dry (*22*).

The reasons for the high accident rate on wet roads are made clear by a comparison of properties of roads and habits of drivers. In Fig. 4 such a comparison is shown as a composite plot of data derived from several sources. Curve 1 represents the net accelerations required to round a curve, for a sample of some 820 vehicles (*7*, p. 511). Curve 2 is a summary of the coefficients of friction for some 900 roads, and curve 3 is a plot of the relative frequency of accidents as a

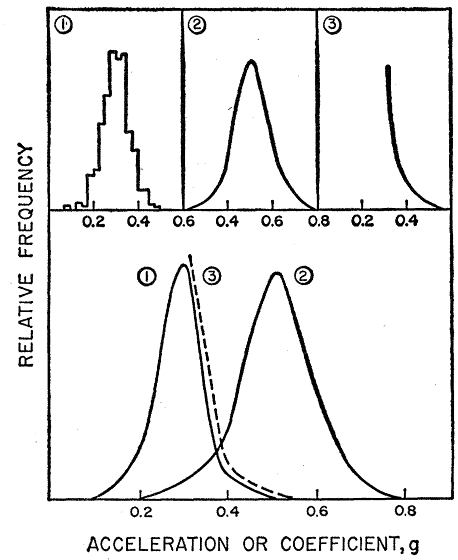

Fig. 4. Comparison of (curve 1) net acceleration required (that is, relative friction required) by a moving vehicle in rounding a turn, (curve 2) coefficients of friction for a large sample of wet roads, and (curve 3) relative risk of a skidding accident.

function of the available friction between tire and road surface (*6*) as determined at the sites of accidents. It is a plausible assumption that curves 1 and 2 are generally representative of friction needs and friction available on wet roads, an assumption reinforced by the fact that curve 3 closely parallels the high side of the "friction need" curve. The close coincidence may exist because drivers make no adjustment for the wetness of the road. There is evidence that, in freely moving traffic, vehicle speeds are essentially the same on wet and on dry pavement (*23*). The overlap of curves 1 and 2 therefore represents a potential for the occurrence of accidents which would not occur on dry roads—a potential applicable to about 90 percent of all drivers and 50 percent of all roads. This set of data explains why weather is the most important single identifiable factor in traffic safety.

References and Notes

1. Data not otherwise cited specifically are from a series of seven papers presented at a meeting of the Division of Rubber Chemistry, American Chemical Society, 23–26 April 1968, to be published in *Rubber Chemistry and Technology*.
2. A. Turner, *Science* **105**, 414 (1947).
3. M. E. Merchant, *ibid.* **113**, 443 (1951).
4. F. H. D. Akkerman, unpublished.
5. P. A. Sigler, M. N. Geib, J. H. Boone, *J. Res. Nat. Bur. Std.* **40**, 339 (1948).
6. C. G. Giles, B. E. Sabey, K. H. F. Cardew, in "Symposium on Skid Resistance," *Amer. Soc. Testing Mater. Spec. Tech. Pub. No. 326* (1962); *Rubber Chem. Technol.* **38**, 840 (1965).
7. J. B. Behr, Ed., "Research on Road Safety," *Department of Scientific and Industrial Re-*

search Laboratory Publication (Her Majesty's Stationery Office, London, 1963).
8. K. A. Grosch and G. Maycock, *Trans. Inst. Rubber Ind.* **42**, 280 (1966); *Rubber Chem. Technol.* **41**, 477 (1968); R. Clamroth and W. Heidemann, *Kautschuk Gummi Kunststoffe* **20**, 413 (1967).
9. F. S. Conant and J. W. Liska, *Rubber Chem. Technol.* **33**, 1218 (1960).
10. D. Tabor, *Proc. Roy. Soc. London Ser. A* **229**, 198 (1965); ———, in *Proceedings, First International Skid Prevention Conference* (Virginia Council of Highway Investigation and Research, Charlottesville, 1959), p. 211; ———, *Rubber Chem. Technol.* **33**, 142 (1960); J. A. Greenwood and D. Tabor, *Proc. Phys. Soc. London* **71**, 989 (1958); *Rubber Chem. Technol.* **33**, 129 (1960).
11. See, for example, *Proc. Rubber Technol. Conf. 4th, London* (1963), papers 17–19 and discussion; H. W. Kummer and W. E. Meyer, in "Symposium on Skid Resistance," *Amer. Soc. Testing Mater. Spec. Tech. Pub. No. 326* (1962); H. H. Vickers, *J. Appl. Polymer. Sci.* **6**, 396 (1962); K. A. Grosch, *Proc. Roy. Soc. London Ser. A* **274**, 21 (1963); ———, *Rubber Chem. Technol.* **37**, 386 (1964).
12. F. L. Roth, R. L. Driscoll, W. L. Holt, *J. Res. Nat. Bur. Std.* **28**, 439 (1942); *Rubber Chem. Technol.* **16**, 155 (1943).
13. A. Schallamach, *Rubber Chem. Technol.* **41**, 209 (1968).
14. W. Close, *Highway Res. Board Bull. 302* (1961), p. 18.
15. K. H. Schulze and L. Beckmann, in "Symposium on Skid Resistance," *Amer. Soc. Testing Mater. Spec. Tech. Pub. No. 326* (1962), p. 42.
16. H. H. Bashore, *Rubber Chem. Technol.* **10**, 820 (1937).
17. *1968 Book of ASTM Standards*; part 28: "Rubber; Carbon Black: Gaskets" (American Society for Testing and Materials, Philadelphia, Pa., 1968), p. 1009.
18. M. L. Williams, R. F. Landel, J. D. Ferry, *J. Amer. Chem. Soc.* **77**, 3701 (1955).
19. B. E. Sabey and G. N. Lupton, *Rubber Chem. Technol.* **37**, 878 (1964).
20. *Proceedings, First International Skid Prevention Conference* (Virginia Council of Highway Investigation and Research, Charlottesville, 1959), pp. 9, 31, 45.
21. A. O. Peterson and H. L. Michael, *Purdue Univ. Extension Ser.* **119**, No. 5, 4 (1965); CE reprint No. 225.
22. J. R. Cunningham, unpublished note, 1966.
23. W. R. Stohner, *Highway Res. Board Bull. 139* (1956), p. 79.
24. We thank the many who helped us in this research: John Mayer, Jr., for technical assistance; the Research Center Mathematics Research and Services group; staffs of the U.S. Rubber Tire Company Development Department, the Laredo, Texas, Proving Grounds of Uniroyal, Inc.; officials and engineers of the New Jersey, New York City, New York State, and Florida highway departments and of the New Jersey Turnpike Authority; officials and police officers of the New Jersey State Police and of the following New Jersey communities: Allendale, Butler, Clifton, East Paterson, Glen Rock, Hawthorne, Lincoln Park, and Wayne.

Congress and the Science Budget

Herbert Roback

Congress makes the laws of the land and in this sense gives final form to national policies and their organizational underpinnings. Whether the Legislative or Executive branch takes the initiative in developing any given policy or organization is less important than the adequacy of its response to national need. If the need is sufficiently compelling, the two branches of government will be in accord that action must be taken. They may differ in important details—there is give and take—but between them national policy finally is hammered out or delicately wrought. A law is written, an organization created, and the course of governmental action set for years to come.

Legislative milestones in science and technology stand out more clearly after World War II. Two immediate postwar problems were: how to conserve the resources and sustain the momentum of war-induced scientific research; and, more pointedly, how to organize and control the future development of atomic energy. The problem of atomic energy was more urgent, because it carried not only the sinister potential of mass destruction but the bright promise of mass benefit through power development and other peaceful applications. The Atomic Energy Commission was established in the year after the war ended, but the debates which eventually established the National Science Foundation as the key support agency for basic research dragged on for 5 years.

In the 1950's there were other milestone enactments. These were, in a sense, the panic years, with missile and space technologies in the forefront. The National Aeronautics and Space Administration, created in 1958, was an immediate answer to Sputnik. The same year the Advanced Research Projects Agency and the Directorate of Research and Engineering were established in the Department of Defense. Spurring these new organizations was a quest for national security interwoven with national prestige and welfare. Although NASA's mission, for example, was stated in terms of peaceful space exploration, in the public mind Sputnik posed a military menace, because it denoted Soviet mastery of large booster technology and complex space systems which had military import.

Our crash programs for ICBM's achieved a formidable defense posture, and the ambitious Apollo program demonstrated dramatically our entry into the space race. Thereafter, in the 1960's, the government became increasingly involved in the welfare field. The technologies, techniques, and resources applied to missile and space development were examined for their application to social problems. Aerospace contractors began to work on such prosaic problems as garbage disposal and traffic congestion or on such esoteric ones as an artificial heart or a teaching machine.

New government departments were established to deal with housing and transportation. Within existing departments new agencies and organizations sprang up to put science and technology to work for the Great Society. More and more research emphasis was given to traffic safety, urban transportation, air and water purification, public health, crime prevention, and scores of other problem areas which received legislative and executive attention. The larger action agencies, created in response to acute national needs, develop vast technical infrastructures to support their missions. They build laboratories, let contracts, and acquire constituencies in business, professional, and academic circles. They attract community and regional support for the jobs and payrolls they provide and they gain advocates in Congress.

As technical empires expand, programs proliferate and agencies compete for technical talents and contractor re-

The author is the staff administrator of the Military Operations Subcommittee of the House Committee on Government Operations. This article is adapted from an address given 28 December 1967 at the AAAS meeting in New York.