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ANALYSIS OF PERFORMANCE RATINGS FOR TIRES

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16. Abstract

This study analyzed two sets of performance ratings for light-duty-vehicle tires. The aim was to ascertain whether some of the ratings in either set convey redundant information. The first set included the Uniform Tire Quality Grade (UTQG) ratings for 2,734 tires, published by the U.S. National Highway Traffic Safety Administration. The second set consisted of ratings for 49 tires published by Consumer Reports. The approach consisted of using factor analysis to determine whether the number of variables in the two sets (3 in UTQG, and 11 in Consumer Reports) can be reduced to a smaller number of independent factors.

The results indicate that the three UTQG variables form two factors. The first is dominated by tread properties, while the second factor reflects tread-abrasion resistance. The two factors accounted for 83% of the variance.

The 11 Consumer Reports variables form four factors. These factors are dominated, in turn, by tread properties, the tire (and especially belt) construction, tread-band flexibility (particularly in the longitudinal direction), and tread-abrasion resistance. Each of the 11 variables loaded highly on at least one factor. The four factors accounted for 68% of the variance.

The examination of the factors in each analysis suggests that each factor that is highly loaded by more than one variable represents richer and more complex information than what smaller subsets of variables could capture. Therefore, none of the variables could be excluded if one wants to provide the same information conveyed by the full sets of the variables.

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Michael Sivak designed the study and the statistical analyses. Marion Pottinger (M'gineering LLC) prepared the discussion.

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Introduction

This study analyzed two sets of performance ratings for light-duty-vehicle tires. The aim was to ascertain whether some of the ratings in either set convey redundant information. The first set included the Uniform Tire Quality Grade (UTQG) ratings for 2,734 tires, published by the U.S. National Highway Traffic Safety Administration. The second set consisted of ratings for 49 tires published by Consumer Reports. The approach consisted of using factor analysis to determine whether the number of variables in the two sets (3 in UTQG, and 11 in Consumer Reports) can be reduced to a smaller number of independent factors.

Method

Analyses employed

Factor analysis with Varimax rotation was performed to reduce the number of variables to a minimum of orthogonal factors. This analysis was supplemented with a pairwise correlational analysis.

Data sets

Uniform Tire Quality Grade (UTQG)

The U.S. Department of Transportation requires tire manufacturers to grade their tires using the Uniform Tire Quality Grading (UTQG) System (NHTSA, 2012). This system provides consumer guidelines for making relative comparisons when purchasing new tires. The tires are graded in the following three areas:

- *Treadwear* grades are an indication of a tire's relative wear rate. The higher the treadwear number is, the longer it should take for the tread to wear down. For example, a tire grade of 400 should wear twice as long as a tire grade of 200.
- *Traction* grades are an indication of a tire's ability to stop on wet pavement. A higher graded tire should allow the driver to stop on wet roads in a shorter distance than a tire with a lower grade. Traction is graded from highest to lowest as *AA*, *A*, *B*, or *C*.
- *Temperature* grades are an indication of a tire's resistance to heat. Sustained high temperature (for example, driving long distances in hot weather) can cause a tire to deteriorate, leading to structural failures such as tread separations. From highest to lowest, a tire's resistance to heat is graded as *A*, *B*, or *C*.

The online file included grades for 4,344 tires (NHTSA, 2012). However, when more than one entry (for different tire sizes) was included for a specific brand and tire line combination with identical wear, traction, and temperature grades, these entries were collapsed into one single entry. (Most entries in the data file already note that the specifications listed are either applicable to a specific range of sizes or to all sizes of that brand and tire line combination.) Furthermore, four tires were not graded on one of the three variables. As a result, the final set included 2,734 tires.

Consumer Reports tire ratings

Consumer Reports (2012) provides tire rating using a variety of variables (tests). This analysis used the following safety variables:

- *Dry braking*: from 60 to 0 mph
- *Wet braking*: historically this has been from 40 to 0 mph, but with the November 2011 report it has changed to 60 to 0 mph
- *Handling*: how well the tire grips in an avoidance maneuver involving a swerve into the left lane and back into the right lane; dry and wet cornering grip; and subjective steering feel
- *Hydroplaning*: how quickly one can drive through standing water before the tires start losing contact with the payment
- *Snow traction*: reflects the distance needed to accelerate from 5 to 20 mph on moderately packed snow
- *Ice braking*: braking on a skating rink from 10 to 0 mph
- *Speed rating*: the maximum speed at which the tire can carry a load corresponding to its load index

Also included in the analysis were four non-safety variables related to fuel efficiency, tread life, comfort, and noise:

- *Rolling resistance*: measured on a dynamometer
- *Tread life*: wear potential on a federal government's treadwear course
- *Ride comfort*: on-road comfort
- *Noise*: on-road noise

Consumer Reports rates tires in nine categories (all season, all season truck, performance all season, ultra high performance all season, ultra high performance summer, all terrain truck, winter, performance winter, and winter truck). The present analysis used two of these categories (all season and all season truck). This selection was based on two considerations. First, not all tire categories used the same variables. Second, the ratings are relative to a standard within a tire category. (It was assumed that the two selected categories had relatively similar standards.)

There were 49 tires that were in one of the two selected tire categories and that were rated on all selected variables (Consumer Reports, 2012).

Results

Uniform Tire Quality Grade (UTQG)

A factor analysis indicated that the three variables (treadwear, traction, and temperature) formed two factors (see Table 1). Factor 1 was loaded highly by both temperature and traction, both with positive factor loadings (.86 and .84, respectively). The pairwise correlation between these two variables (see Table 2) was $r = .45$. Factor 2 was loaded highly only by treadwear, with a positive factor loading (.98).

Factor 1 accounted for 48% of the total variance. Both factors accounted for 83%.

Table 1
Factor structure for the three UTQG variables.
(The entries are factor loadings.)

Variable	Factor	
	1	2
Treadwear	.01	.98
Traction	.84	.22
Temperature	.86	-.19

Table 2
Pairwise correlations among the three UTQG variables.
(The entries are correlation coefficients.)

	Treadwear	Traction	Temperature
Treadwear	1	.13	-.08
Traction	.13	1	.45
Temperature	-.08	.45	1

Consumer Reports tire ratings

A factor analysis indicated that the 11 variables formed four factors (see Table 3). The factors, the highest loading variables, and the factor loadings are as follows:

- Factor 1
  - Ice braking (-.70)
  - Rolling resistance (-.69)
  - Dry braking (.63)
  - Hydroplaning (.63)

- Factor 2
  - Speed rating (.79)
  - Handling (.78)
  - Wet braking (.59)
  - Noise (.55)

- Factor 3
  - Ride comfort (.84)
  - Snow traction (.68)
  - Dry braking (.54)

- Factor 4
  - Tread life (.92)

Table 3
Factor structure for the 11 Consumer Reports variables.
(The entries are factor loadings.)

Variable	Factor			
	1	2	3	4
Dry braking	.63	.25	.54	.12
Wet braking	.44	.59	.22	.44
Handling	.37	.78	-.05	.24
Hydroplaning	.63	.25	.14	-.01
Snow traction	-.09	-.13	.68	.27
Ice braking	-.70	-.31	.20	.29
Speed rating	-.02	.79	-.10	-.29
Rolling resistance	-.69	.07	.12	.06
Tread life	-.16	-.06	.10	.92
Ride comfort	-.03	.03	.84	-.01
Noise	.16	.55	.50	-.12

Factor 1 accounted for 31% of variance. The cumulative variance accounted for by adding the other factors was 50% with Factor 2, 59% with Factor 3, and 68% with Factor 4.

The pairwise correlations among the 11 variables are listed in Table 4.

Table 4
Pairwise correlations among the 11 Consumer Reports variables.
(The entries are correlation coefficients.)

	DB	WB	HA	HY	ST	IB	SR	RR	TL	RC	NO
Dry braking (DB)	1	.62	.39	.46	.20	-.36	.08	-.21	.02	.39	.45
Wet braking (WB)	.62	1	.63	.33	.09	-.32	.25	-.19	.24	.18	.47
Handling (HA)	.39	.63	1	.43	-.04	-.42	.51	-.22	.06	.02	.36
Hydroplaning (HY)	.46	.33	.43	1	.10	-.41	.19	-.18	-.10	.02	.25
Snow traction (ST)	.20	.09	-.04	.10	1	.33	-.09	.06	.28	.40	.09
Ice braking (IB)	-.36	-.32	-.42	-.41	.33	1	-.29	.34	.35	.10	-.19
Speed rating (SR)	.08	.25	.51	.19	-.09	-.29	1	-.15	-.26	-.02	.23
Rolling resistance (RR)	-.21	-.19	-.22	-.18	.06	.34	-.15	1	.14	.04	-.06
Tread life (TL)	.02	.24	.06	-.10	.28	.35	-.26	.14	1	.16	-.08
Ride comfort (RC)	.39	.18	.02	.02	.40	.10	-.02	.04	.16	1	.30
Noise (NO)	.45	.47	.36	.25	.09	-.19	.23	-.06	-.08	.30	1

Discussion

For both analyses, variables that load most highly on each factor will be discussed in the context of the known structural or material parameters of tires. The parameter set most important for each variable is discussed, but every inherent performance compromise required in commercial tires is not fully considered. The most important tire design parameters for each variable are highlighted in Tables 5 and 6. (The color shading in these tables highlights related parameters both within each table and across both tables.)

Variable clustering: UTQG

Factor 1

Factor 1 (in Table 1) involves two variables (tests) that are strongly tread affected (see Table 5). However, the most desirable characteristic for good performance in one test, high hysteresis at high frequencies, is different from the crucial compound parameter for good performance in the other test, low hysteresis at low frequencies. This implies that the best combined performance will come from a specially designed tread compound, as is the case.

Table 5
Relevant parameters for the variables in the two UTQG factors.
(Color shading highlights related parameters.)

Factor	Variable	Parameter
1	Traction	Large high-Hz tread compound hysteresis
		Deeper tread depth/open tread design
		Higher aspect ratio
	Temperature	Small low-Hz tread compound hysteresis
		Lower tread depth/open tread design
		Higher speed capable belt/carcass design
2	Treadwear	Good compound abradability
		High cornering stiffness
		High tread depth + closed tread design

The UTQG traction grade is most strongly governed by the tread compound hysteresis (the lag in response to changes in the forces) at high frequencies (100,000 to 1,000,000 Hz) where large hysteresis is desirable. As the UTQG traction grade involves testing at a low water depth and modest speed, the tread depth and design are secondary factors in the UTQG traction results so long as they are adequate. (Low aspect ratio can be a negative factor in wet traction tests for the reasons noted later under hydroplaning in the discussion of Factor 2 in Table 3, but is not likely to be detectable under the conditions used in the UTQG grading test.)

The UTQG temperature grade is usually related to test termination due to belt edge or tread separation, where excessive operating temperature is the most important factor. Studies of rolling resistance (see Factor 1 in Table 3) indicate that at least half of the tire's energy consumption and heat generation come from stress and strain cycling of the tread and belt area. The tread and belt contribution is most strongly governed by the tread compound hysteresis at frequencies below 100 Hz, where it is desirable that hysteresis be as small as possible. It is important that the tread mass also be as low possible consistent with other performance requirements. The belt/carcass design effect on temperature is crucial as speed rises (for reasons discussed later for speed rating [see Factor 2 in Table 3]), but the UTQG temperature grading test is not aggressive enough to cause this to dominate as it will in the speed rating test.

Factor 2

Factor 2 (in Table 1) reflects tread-abrasion resistance and is strongly influenced by tread-compound stiffness and other tire-construction features, which determine the tire-cornering stiffness—the most crucial feature in the low slip-angle force-and-moment properties of the tire.

The UTQG treadwear grade is an attempt to characterize a tire construction's overall or average rate of wear compared to a standard construction, when driving in a defined way over a specified test route. (It does not explicitly consider wear unevenness, which usually manifests itself as ride vibration or undesirable noise.)

UTQG treadwear is most strongly governed by the tread compound's abradability, a property characterizing how rapidly the tread loses particles under specified shear-energy input during operation. In turn, abradability depends on the compound design. (Unfortunately, there are many different abrasion tests and no agreement that one is the universal standard.)

Almost all driving occurs under conditions involving slip angles below one degree where the most important tire force-and-moment property is cornering stiffness. The sliding motion of tire tread locations over the road surface is determined by the tire construction's cornering stiffness interacting with the vehicle's dynamics, when driving the test course. If the resulting slip angles during operation are reduced by appropriate tire force-and-moment properties, tire wear is limited because the motion of tread surface elements relative to the road, and consequent shear energy the tread surface experiences are reduced. Cornering stiffness and tread element stiffnesses are motion determinates.

Obviously, greater tire tread life will be associated with greater tread depth, all else being equal. However, as will be discussed later, adding tread depth has drawbacks.

Variable clustering: Consumer Reports

Factor 1

Factor 1 (in Table 3) is dominated by tread properties, but not the same properties for each variable (see Table 6).

Ice braking involves straight line stopping at low speed without ABS at 25 to 27° F. Near freezing ice has a tendency to be coated with a thin layer of water so far as the tire is concerned. Thus, driving on ice acts like operation over a boundary layer atop a smooth tile unless there is something to break the water layer. It helps to have a lot of edges perpendicular to the tire's path to move any existing water film; many sipes and more footprint length helps. A low glass-transition-temperature rubber, like natural rubber, is superior on ice.

Table 6
Relevant parameters for the variables in the four Consumer Reports factors.
(Color shading highlights related parameters.)

Factor	Variable	Parameter
1	Ice braking	Tread design with many transverse edges
		Low T_G tread compound
		Higher aspect ratio
	Rolling resistance	Small low-Hz tread compound hysteresis
		Low tread mass (low depth + open tread design)
	Dry braking	Large high-Hz tread compound hysteresis
		Closed tread design
	Hydroplaning	Deeper tread depth + open tread design
		Higher aspect ratio
		Modestly stiff tread compound
2	Speed rating	Standing wave inhibiting belt + carcass design
		Lower tread depth + open tread design
		Small low-Hz tread compound hysteresis
	Handling	High in plane belt bending stiffness
		Low aspect ratio
		Low tread depth + closed tread design
		High tread compound stiffness
	Wet braking	Deep tread depth + open tread design
		Higher aspect ratio
		Large high-Hz tread compound hysteresis
		High cornering stiffness
		High tread depth + closed tread design
	Noise	Low out of plane bending stiffness
		Carcass with appropriate modal frequencies
		Proper tread design
3	Ride comfort	Low out of plane bending stiffness
		Carcass with appropriate modal frequencies
		Higher aspect ratio
	Snow traction	Tread design with many flexible elements
		Higher aspect ratio
		Low T_G tread compound
	Dry braking	Large high-Hz tread compound hysteresis
		Low tread depth + closed tread design
4	Tread life	Good compound abradability
		High cornering stiffness
		High tread depth + closed tread design

Tire rolling resistance rating is based on SAE J1269 test results. For passenger radial tires, the rolling resistance is one-half or more determined by hysteretic energy dissipation in the tread and belt area at frequencies under 100 Hz. The tread compound hysteresis and mass are first-order tire influences on rolling resistance results. The tread hysteresis at low frequencies should be small by design. (If rolling resistance were the only concern, tread depths should be very small.) Since the J1269 test, used in this case, is run at 50 mph, construction features incorporated to obtain speed rating only influence the rolling resistance rating as an addition to thickness in the tread/crown region and indeed increase rolling resistance in the J1269 test.

Dry braking is primarily an effect of tread compound hysteresis at high frequencies, 100,000 to 1,000,000 Hz. It is desirable to put as much tread on the road as possible under dry conditions, which says that a very closed tread design, and a relatively compliant tread and belt area in terms of envelopment are best for this feature. The racing slick is the logical design in dry conditions on a clean road surface.

Hydroplaning is tread dependent, but here the dominant factors are tread design and depth at a given tire aspect ratio. The Consumer Reports test looks at deviation from a circular path on encountering a puddle of defined depth and extent. Fundamentally, if the water can get out from under the tread elements while they are in the tire contact, hydroplaning will not occur. The design requirement is tread grooves and sipes into which the water under the tread elements can drain rapidly enough to allow the tread surface to contact the road surface before a tread element leaves the tire footprint. Plainly, there must be enough grooves and sipes in combination with adequate groove and sipe depths. The grooves and sipes must also be at short enough distances from the centers of tread elements that the water can flow into them before the tread element being drained leaves contact. Aspect ratio plays a part in this because the shorter the footprint the less time is available for the water to drain into the grooves and sipes. Aspect ratio also affects the footprint bow wave. Low aspect ratio tires are not the best for hydroplaning resistance, all else being equal in terms of tread design and depth. A modestly stiff tread compound is required to prevent water from puddling under the tread elements rather than draining into the grooves and sipes.

Factor 2

Factor 2 (in Table 3) is a set of variables (tests) in which the tire construction in general and the belt construction in particular tend to be very important (see Table 6).

Speed rating for radial tires is largely dependent on development of vibrations excited at the rear of contact that, when viewed by a stationary observer, appear to be waves standing on the tire surface. In effect, these vibrations cause the tire material to be subjected to additional stress/strain cycles during each rotation beyond the one due to tire/road contact. This greatly increases tire tread and belt temperature. The structural design of tires to incorporate features like belt cap plies and carcass modifications that increase modal natural frequencies delay the onset of these vibrations, raising the speed rating. Low tread hysteresis at the frequencies involved is important, but it is best to prevent standing waves from occurring in the speed range in which it is intended to use the tire.

Handling rating is a subjective evaluation determined in a simulated avoidance maneuver that involves a double lane change, two lane changes one following the other in a short time period. A real world equivalent would be coming on a parked car in your lane that you did not did not see before you were too close to stop. This rating is primarily a function of tire force and moment, with cornering stiffness being a good first-order tire parameter related to the results of this test. A low aspect ratio tire with a belt that has high lateral bending stiffness and also has high tread stiffness, has a high cornering stiffness and will do well in this test. (The cornering stiffness behavior is basically mimicked at slip angles below the angle associated with the lateral force peak.)

Wet braking is characterized by vehicle stopping distance measured on a wetted pavement. The test is run with ABS active, and the results depend on peak performance, not slide as in UTQG grading. Good performance is dependent on good drainage from beneath the tire tread in the same sense as in hydroplaning studies. The final result, after the water layer is reduced to boundary layer depth, is dependent on the frictional properties of that part of the tread which finally comes into contact with the road through action of the road microtexture and, therefore, on the compound hysteresis at high frequencies.

Noise is perceived loudness within the vehicle passenger compartment when operating on a variety of different pavement textures. This is mostly due to structural transmission of tread/pavement generated vibration into the passenger compartment. Low out-of-plane bending stiffness in the tread and belt tends to reduce the inputs to the tire structure from road irregularities. (The same comment applies for ride comfort, but at lower frequencies.) The structural modes of the tire, which are lightly damped, are important determinants of what vibration reaches the vehicle spindles at noise frequencies from the first tire-radial-bending mode upward. If the tire modal frequencies closely match those of the vehicle, the tire will be very loud in this test. The tire also generates airborne noise. The airborne noise level perceived by vehicle occupants depends on the tire tread pattern design and the road texture, with the sound transmission depending on vehicle passenger compartment air tightness.

Factor 3

Factor 3 (in Table 3) is a set of variables (tests) in which tread band flexibility, particularly in the out-of-plane direction, is most important (see Table 6).

Ride is perceived discomfort below 100 Hz when operating on a variety of different pavement textures. Thus, ride in the context of this rating is a judgment of harshness, vibration induced by tire interaction with road surface irregularities. These are occupant perceptions of structural vibration including spring-mass-damper vehicle behavior, and the first mode or two of tire radial and longitudinal vibration. Low out-of-plane bending stiffness in the crown is desirable as it improves envelopment of road irregularities reducing input force levels. A higher aspect ratio, lower belt bending stiffness, and lower tread stiffness in the longitudinal direction will all contribute to better enveloping through reduced out-of-plane bending stiffness in the crown. If the tire modal frequencies closely match those of the vehicle, and/or the tire is stiffer radially than the general tire population evaluated in a particular comparison, the tire will be judged to be harsh. Structural details of the tire carcass, including aspect ratio, affect tire modal natural frequencies and are the determinants of radial stiffness—a major determinant of spring-mass-damper vehicle vibration.

Snow traction is a measure of the time required to accelerate from about 5 to 20 mph on medium hard packed snow. The tire traction in this case arises from having a large part of the tread grooving and siping transverse to the direction of motion. This area deforms the snow surface generating ridges in or on the surface that act like teeth on a rack. The tire then interacts with the ridges, as if it were a pinion, producing the driving force. This process works best if there are numerous transverse edges present on the tread pattern, as is desirable for ice traction, and if the tread pattern cleans well, the snow falls out of the pattern, so that the tire grooves and sipes remain available to interact with the snow surface. This means that tread elements must bend flexibly in the direction of motion for good snow traction. There is a need for distance in the footprint for the required interactions to occur so a higher aspect ratio will be better. Tread compound with a lower glass transition temperature is better on ice. Therefore, it will be better here as well, because ice is often present along with snow.

Dry braking was considered under Factor 1. It likely reappears here because, like ride and snow traction, it is helped by good tread surface conformance to the test surface.

Factor 4

Factor 4 (in Table 3) is analogous to Factor 2 in Table 1, with the same relevant parameters (see Table 6). The difference is that the Consumer Reports test is different in detail than the UTQG test and, therefore, leads to somewhat different answers.

Problems with elimination of variables

The question of interest in this study is whether the three UTQG variables and the 11 Consumer Reports variables could each be reduced into smaller subsets of variables without losing some relevant information. Indeed, the present analyses suggest that the UTQG ratings cluster into two factors, and the Consumer Union variables cluster into four factors. However, this clustering, by itself, is not sufficient to justify elimination of any variables. This is the case because each factor could be richer in its properties than what any single variable could capture. Furthermore, as will be discussed below, it is not only the case that we need more than two variables for evaluating the UTQG space and four variables for evaluating the Consumer Reports space, but we need all variables to provide the information intended.

The UTQG Factor 1 is loaded most highly by the *traction* and *temperature* grades. Both of these variables are tread dependent. Unfortunately, the important tire design parameters for one are either not considered for the other or are actually related to crucial performance in an opposite way. For example, a good temperature grade depends on small low-Hz tread compound hysteresis, but a good traction grade depends on large high-Hz compound hysteresis. Neither variable addresses the other property. (As shown in Table 2, the pairwise correlation between the traction and temperature grades, $r = .45$, is only moderate.)

The Consumer Reports Factor 1 is loaded most highly by *ice braking*, *rolling resistance, dry braking*, and *hydroplaning*. Again, the tread and belt properties dominate. However, again the important tire design parameters for one variable are either not considered for the other or are related to crucial performance in an opposite way, consistent with the fact that two of the variables (ice braking and rolling resistance) have negative loadings on this factor. For example, good ice braking depends on the majority tread edges being perpendicular to the direction of motion. That indicates that more than a usual amount of the tread void is perpendicular to the direction of motion, and this does not work as well for hydroplaning as having the direction parallel to the direction of motion. Likewise, it helps ice braking if the tread elements are as flexible in longitudinal bending as squeegee blades, but that hurts dry braking as the area of the tread rubber in the shear interface against the road will be reduced. Low rolling resistance depends on small low-Hz tread compound hysteresis, but is independent of high-Hz compound hysteresis for which large values are crucial for dry traction. A low tread depth is good for rolling resistance and bad for hydroplaning. Hydroplaning is independent of tread compound hysteresis, but does depend to some extent on compound stiffness or hardness, as well as having reasonable tread element stiffness due to the tread pattern's mechanical design. Ice traction is best when the tread compound has a low glass transition point as occurs for compounds based on natural rubber. However, these compounds do not have the traction at higher temperatures shown by tread compounds using higher glass transition rubbers such as Styrene-butadiene rubbers. (As shown in Table 4, the pairwise correlations among these variables are all either weak or only moderate, with the strongest one being $r = .46$. Consistent with the fact that ice braking and rolling resistance have negative loadings on this factor, the pairwise correlations between either of these two variables, and either of the other two variables [dry braking and hydroplaning] are negative.)

The Consumer Reports Factor 2 is loaded most highly by *speed rating, handling, wet braking*, and *noise*. Two of these variables (handling and noise) are subjective ratings. The other two variables are objective measurements. Speed and handling ratings have a positive relationship because the customer for one is usually a customer for the other, so both are designed into the same tire product. The precise design parameters for both need not appear together and one can appear without the other. Examination of the parameter column in Table 6 illustrates this. Note that for handling, a dry surface test, a small amount of groove area is ideal. In contrast, wet braking works best with a deep, open tread and higher aspect ratio, and is in direct contrast with handling and speed rating for tires designed to ideally consider one variable over the other. It is also worth noting that perceived handling is highly dependent on vehicle sideslip angle remaining low (reducing the fright factor). Noise rating is a different issue altogether. The auditory impression of the product, as filtered by the test vehicle, is a subjective judgment. A slightly higher loudness that causes one frequency to stand out more can determine this rating. In this case, higher tire bending modal frequencies are probably not desirable because of human auditory sensitivity, but they certainly help with speed rating. (As shown in Table 4, the pairwise correlations among these variables are all moderate, with the strongest one being $r = .63$.)

The Consumer Reports Factor 3 includes *ride comfort, snow traction*, and *dry braking* as variables. These have good tread band flexibility in a circumferential direction as a common factor. However, there is no association among these variables in several ways. For example, good snow traction is not associated with high dry surface friction, which is required for good dry braking performance. Indeed, the desirable tread features for snow and dry traction are diametrically opposed to each other. Ride comfort is a subjective judgment dependent on tire vertical stiffness and the first modal natural frequencies, and it has nothing to do with friction. (As shown in Table 4, the pairwise correlations among these variables are all either weak or only moderate, with the strongest one being $r = .40$.)

Conclusions

This analysis found that the three UTQG variables form two factors. The first UTQG factor, loaded by treadwear and traction, is dominated by tread properties. The second UTQG factor, loaded only by treadwear, reflects tread-abrasion resistance, and is strongly influenced by tread-compound stiffness and other tire-construction properties that determine the tire-cornering stiffness. The two factors accounted for 83% of the variance.

The 11 Consumer Reports variables form four factors. The first Consumer Reports factor is loaded most highly by ice braking, rolling resistance, dry braking, and speed rating. This factor is dominated by tread properties. The second Consumer Reports factor is loaded most highly by speed rating, handling, wet braking, and noise. In this factor, the tire construction in general, and the belt construction in particular, tend to be very important. The third Consumer Reports factor is loaded most highly by ride comfort, snow traction, and dry braking. This factor is dominated by tread-band flexibility, particularly in the longitudinal direction. The fourth factor, loaded only by tread life, is analogous to the second UTQG factor. Each of the 11 variables loaded highly on one factor, except for dry braking, which loaded highly on two factors. The four factors accounted for 68% of the variance.

The examination of the factors in each analysis suggests that each factor that is highly loaded by more than one variable represents richer and more complex information than what smaller subsets of variables could capture. Therefore, none of the variables could be excluded if one wants to provide the same information conveyed by the full sets of the examined variables.

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