Technical Appendix

TECHNICAL APPENDIX

Introduction

This technical appendix is divided into four sections. The first section contains descriptions from Galaxy Scientific Corporation about the equipment, preliminary testing, and methods and procedures they used to conduct the survey of the smoothness of New York City streets. The second section describes how the roughness index categories were determined and what they are. The third section describes the sampling and weighting procedures. The last section describes the estimation and computation of standard errors, and provides examples from the survey.

I. THE MEASUREMENT OF THE CITY'S STREETS

This section, drafted by Galaxy Scientific Corporation, describes the field measurements of New York City streets. The procedures are based on the methods used for assessing highway pavement roughness developed by an international project sponsored by the World Bank, and on work conducted under the National Cooperative Highway Research Program, the National Research Council and the Federal Aviation Administration.

Background of the Study of Pavement Roughness

Prior to the introduction of newer technologies, a straightedge was used as the sole indicator of pavement smoothness. During the late 1950's the concept of "serviceability", defined as the ability of a pavement to serve the traveling public, was developed during the American Association of State Highway and Transportation Officials (AASHTO) road test. Since then the most common measure of serviceability has been the Present Serviceability Index (PSI). This measure is primarily suited for evaluation of pavement condition. However, the National Cooperative Highway Research Program observed that "serviceability is not exclusively a measure of pavement rideability or ride quality, but is confounded by the inclusion of factors for surface defects."[1]

In recent years, ride quality has been found to be a stronger measure of the ability of pavements to serve the traveling public. As a consequence, several smoothness-measuring devices have been developed to define standards for and control the quality of new construction. Smoothness-measuring devices currently used in new pavement

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[1] National Cooperative Highway Research Program (NCHRP) Report 308: Pavement Roughness and Rideability Field Evaluation, 1988, Transportation Research Board, National Research Council, Washington D.C, Janoff, M.S.

construction include straightedges, profilographs, and response-type roughness measuring systems and inertial profilers. Transportation agencies use a straightedge in one way or another to evaluate smoothness of both new and existing pavements -- a few as the sole approach to smoothness control, but most as a supplement to other equipment.

During 1987/1988, the Transportation Research Board of the National Research Council sponsored research that developed an equation for correlating longitudinal profiles with rideability, making it possible to use objective measures of a pavement's longitudinal profile to determine its acceptability to the traveling public.[2] At about the same time, the International Road Roughness Experiment sponsored by the World Bank was initiated, consisting of research teams from Brazil, England, France, the United States, and Belgium, to establish guidelines for conducting and calibrating road roughness measurements. The results led to an international standard, the International Roughness Index (IRI)[3] for roughness measurements obtained by response-type road roughness measurement systems (RTRRMS). The measure obtained from a RTRRMS is called average rectified slope, which is a measure of the ratio of the accumulated suspension motion of a vehicle, divided by the distance traveled by the vehicle during the measure. The reference RTRRMS used for the IRI is a mathematical model, rather than a mechanical system, and exists as a computation procedure applied to a measured profile. The computation procedure is called a quarter-car simulation, as illustrated in Figure 1, because the mathematical model represents a RTRRMS having a single wheel. This type of measure varies with the speed of the vehicle. A standard (simulation) speed of 80 km/hr (50 mph) is specified in the definition of the IRI.

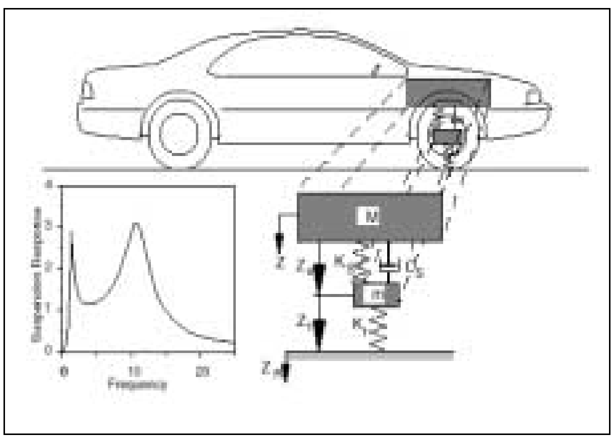


Figure 1. Quarter Car Simulation Model

[2] National Cooperative Highway Research Program (NCHRP) Report 275: Pavement Roughness and Rideability, 1985, Transportation Research Board, National Research Council, Washington D.C, Janoff, M.S., Nick, J.B., Davit, P.S., and Hayhoe, G.F.
National Cooperative Highway Research Program (NCHRP) Report 308: Pavement Roughness and Rideability Field Evaluation, 1988, Transportation Research Board, National Research Council, Washington D.C, Janoff, M.S.

[3] World Bank Technical Paper Number 46: Guidelines for Conducting and Calibrating Road Roughness Measurements, Sayers, M.W., Gillespie, T.D., Patterson, W.D.O

Definitions

The terms used during the course of this project are as follows:

***Cluster*.** A selected length of road surface measured during one recording interval (comprised of 1 to several blocks). See Figure 2.

***Block*.** One physical street length (within a cluster) starting at the beginning of an intersection and ending prior to the start of a second intersection. See Figure 2.

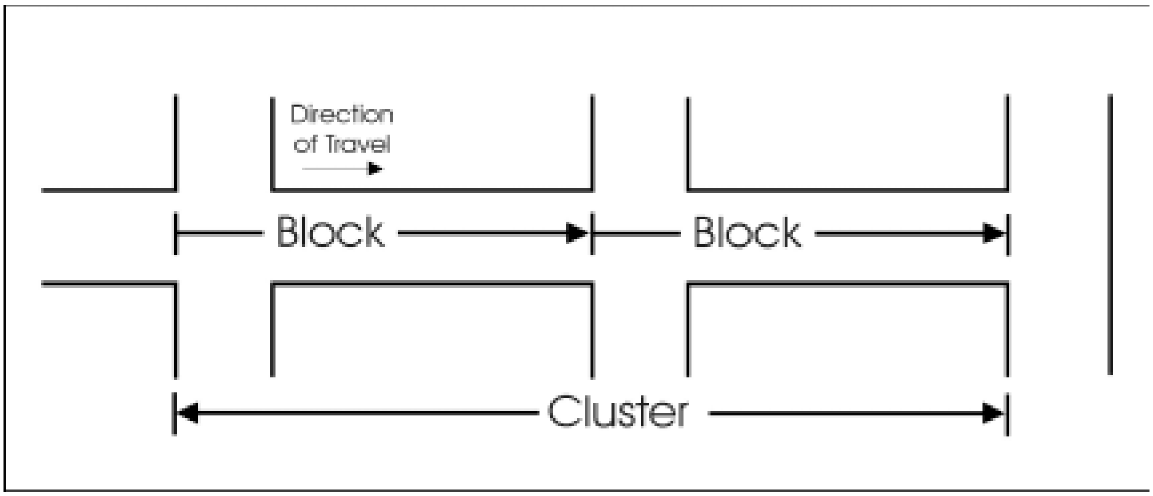


Figure 2. Block and Cluster Diagram

***District*.** One of 59 geographical areas within the five boroughs (Brooklyn, The Bronx, Manhattan, Queens and Staten Island) of New York City. 40 sample clusters were randomly selected by the Fund's sampling expert for testing in each community district.

***IRI*.** The International Roughness Index (IRI) values for this effort were computed using a direct implementation of the computer program listed in World Bank Technical Paper Number 46, "Guidelines for Conducting and Calibrating Road Roughness Measurements," 1986. Clearly, the standard measurement speed of 50 mph specified could not be obtained in the city due to legal speed limits and traffic conditions, hence the Fund is designating the measure a City Roughness Index (CRI).

The IRI index is very useful for relating a roughness measure to overall ride quality. It satisfies the criteria of being time-stable, transportable, and relevant, while also being readily measurable by all practitioners. Figure 3, from World Bank Technical Paper Number 46, shows how IRI measurements on highways vary by the type and condition of the road.

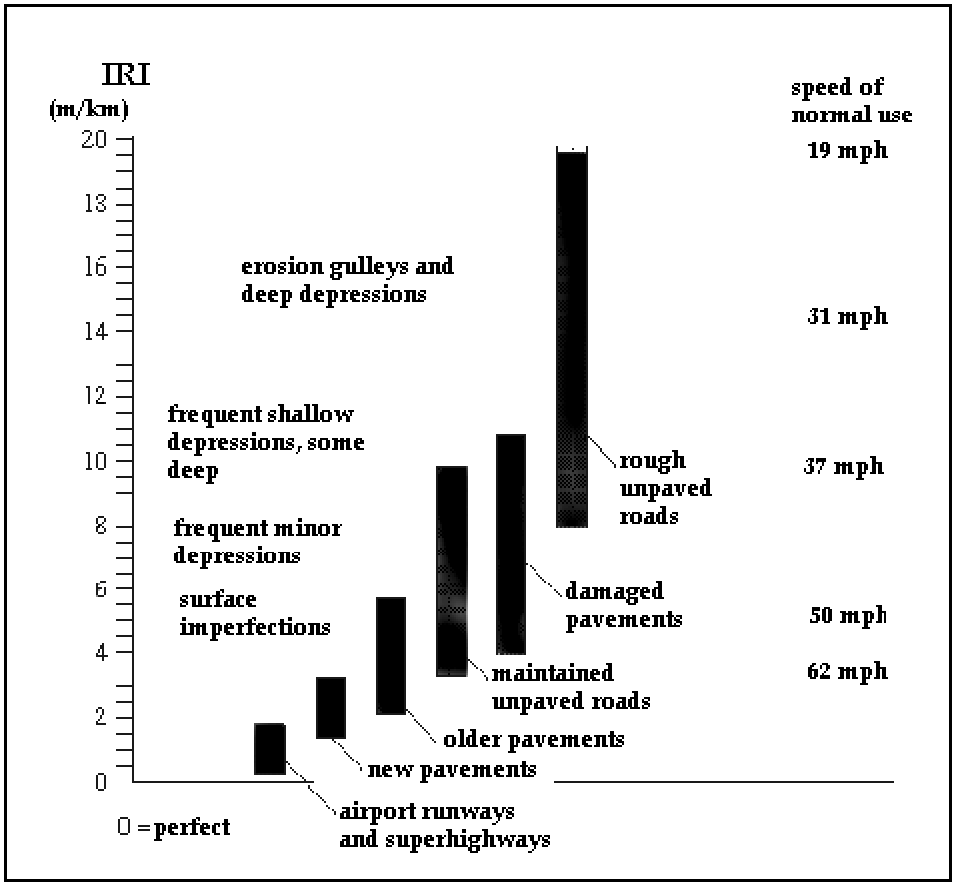


Figure 3. IRI Roughness Scale For Highways

The IRI is also strongly related to the subjective opinions about road roughness that can be obtained from the public. In establishing IRI as a reporting standard, four classes of approaches for measuring road roughness were established (based on the ability of each method to measure IRI precisely and accurately) as follows:

- *Class I - Precision Profiles.* In a Class I survey, the longitudinal profile of the wheelpath is measured manually using a rod and level, Transportation Road Research Laboratory (TRRL) Beam, Face Dipstick, or similar high-precision device. The measured profile is used as a basis for calculating the IRI. A Class I survey provides the highest level of precision and repeatability.

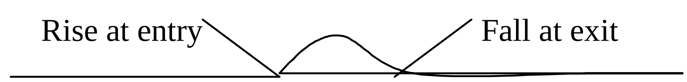
- *Class II - Other Profilometer methods.* In a Class II survey, the profile of one or both wheelpaths is measured using either contact or noncontact profilometers that have been calibrated on sections with profiles determined from a Class I survey. (The equipment used by Galaxy Scientific Corporation for the survey of New York City Streets is a Class II inertial profiling device.)

- *Class III - IRI estimates from correlation equations.* A Class III survey is performed using an RTRRMS or other roughness device such as a rolling straightedge. The measures from these devices must be correlated with IRI using equations developed experimentally for each device. The equipment used in a Class III survey must be calibrated to sections whose profiles have been determined from a Class I or Class II survey.

- *Class IV - Subjective ratings and uncalibrated measures.* Class IV Surveys use subjective evaluations of the roadway that are produced by either riding over the section or by conducting a visual inspection. These evaluations are then roughly correlated with IRI through the use of roadway descriptions for various IRI values. These surveys are considered to be "calibration by description." An uncalibrated RTRRMS may also be used.

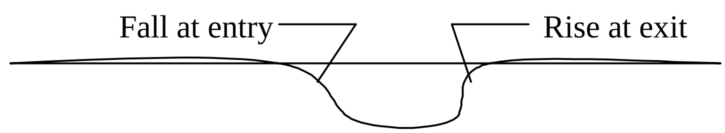
Bumps.[4] For this effort, a "bump" was defined as a deviation from a straightedge at either of two locations: entry and exit. For example, an upward bump would have a rise at the entry point and a fall at the exit as depicted below.

Upward Bump



Conversely, a downward bump, such as a pothole, would have a fall at the entry point and a rise at the exit.

Downward Bump



Additionally, in order for the vehicle to "feel" the bump, the entry and exit points could be no less than a tire print and no more than the distance between the front and rear wheels of the vehicle. For these reasons, a minimum length of ½ foot and a maximum 6-foot straightedge was selected. As a result, only the entry or exit (peak) of a bump with a surface length of less than six feet would be counted and, only the largest bump within six feet of each other (in the same wheelpath) would be counted.

[4] NOTE: The term "jolt" is used by the Fund for the City of New York at times instead of the term "bump" because bump is commonly understood to mean a rise in the surface. We are, in fact, measuring significant upward rises as well as significant downward depressions, both of which create the sensation of a jolt and are the cause of rider's discomfort and dismay. The technical term to describe both upward and downward deviation is "bump."

Bump Index. The Boeing (aircraft) Company has been examining runway roughness for the acceptability of runway roughness to Boeing aircraft. An application of their efforts has been used in the presentation of the bump indexes reported for this project. The basis of the "Boeing Method" is to construct a straightedge between two points on the elevation profile and to calculate:

Bump Height - the maximum vertical distance from the straightedge to the profile sample point for all positions of the straightedge along the profile;

Bump Length - the shorter of the distance from the bump height position to the start of the straightedge and the distance from the end of the straightedge to the bump height position.

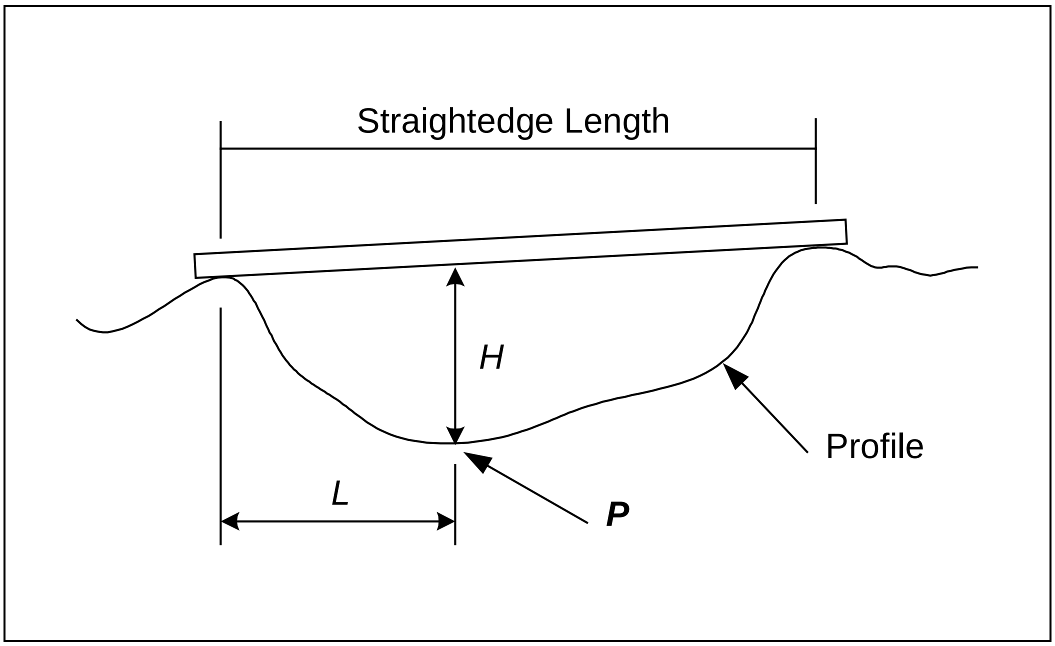


Figure 4. Anatomy Of Bump Index

Figure 4 shows bump height, *H*, and bump length, *L*, for a point ***P*** on a pavement elevation profile. Bump length is always measured from the end of the straightedge closest to the point ***P***.

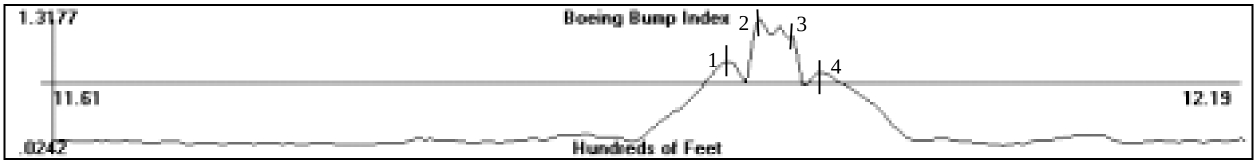
The straightedge length can take any value between defined minimum and maximum lengths (1/2 and 6 feet respectively for this effort).

The bump index at point ***P*** on the profile is defined as: $\frac{H}{H_R}$

Where H_R is a reference limiting bump height as a function of bump length *L*.

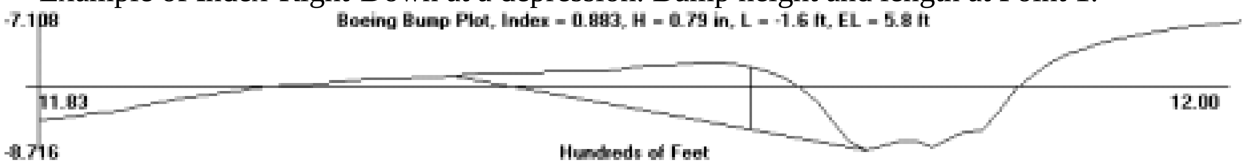
There is a further subdivision into primarily upward disturbances (bumps) and primarily downward disturbances (depressions). The figure above shows a depression.

From the above bump description, there are four possible combinations of bump height and bump length as illustrated on the profile:



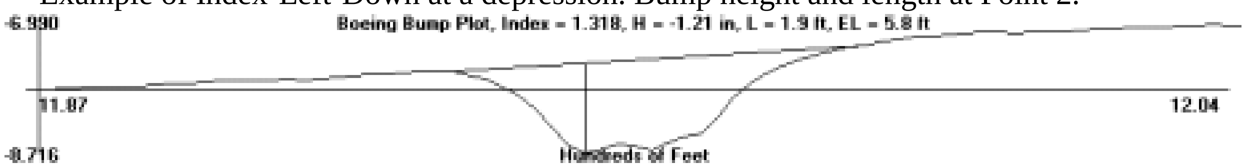
Index-Right-Down has *L* measured to the right hand end of the straightedge and *H* measured downward from the straightedge to ***P*** (negative).

Example of Index-Right-Down at a depression. Bump height and length at Point 1.



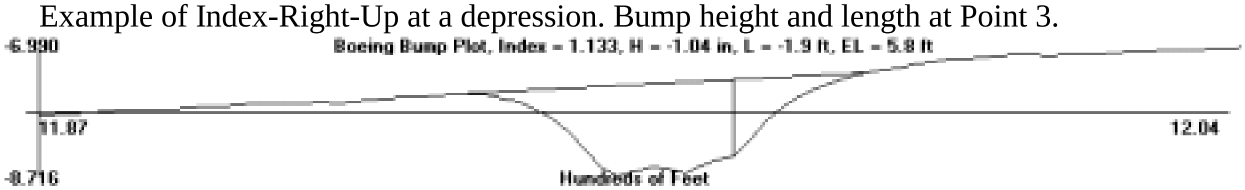
1. Index-Left-Down has *L* measured to the left-hand end of the straightedge and *H* measured downward from the straightedge to ***P*** (negative).

Example of Index-Left-Down at a depression. Bump height and length at Point 2.



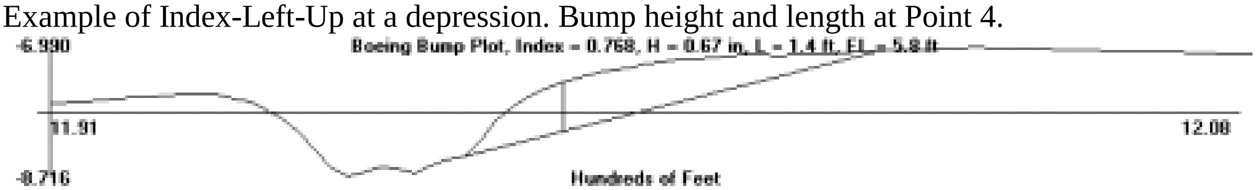
2. Index-Right-Up has *L* measured to the right hand end of the straightedge and *H* measured upward from the straightedge to ***P*** (positive).

Example of Index-Right-Up at a depression. Bump height and length at Point 3.



3. Index-Left-Up has *L* measured to the left-hand end of the straightedge and *H* measured upward from the straightedge to ***P*** (positive).

Example of Index-Left-Up at a depression. Bump height and length at Point 4.



Further investigation may show that this subdivision into left/right/up/down can discriminate between different types of disturbance. However, a single bump index defined as the maximum of the absolute values of all four of the combinations given above was selected. The following profile (Cluster 1X11L) has a number of well-defined depressions:

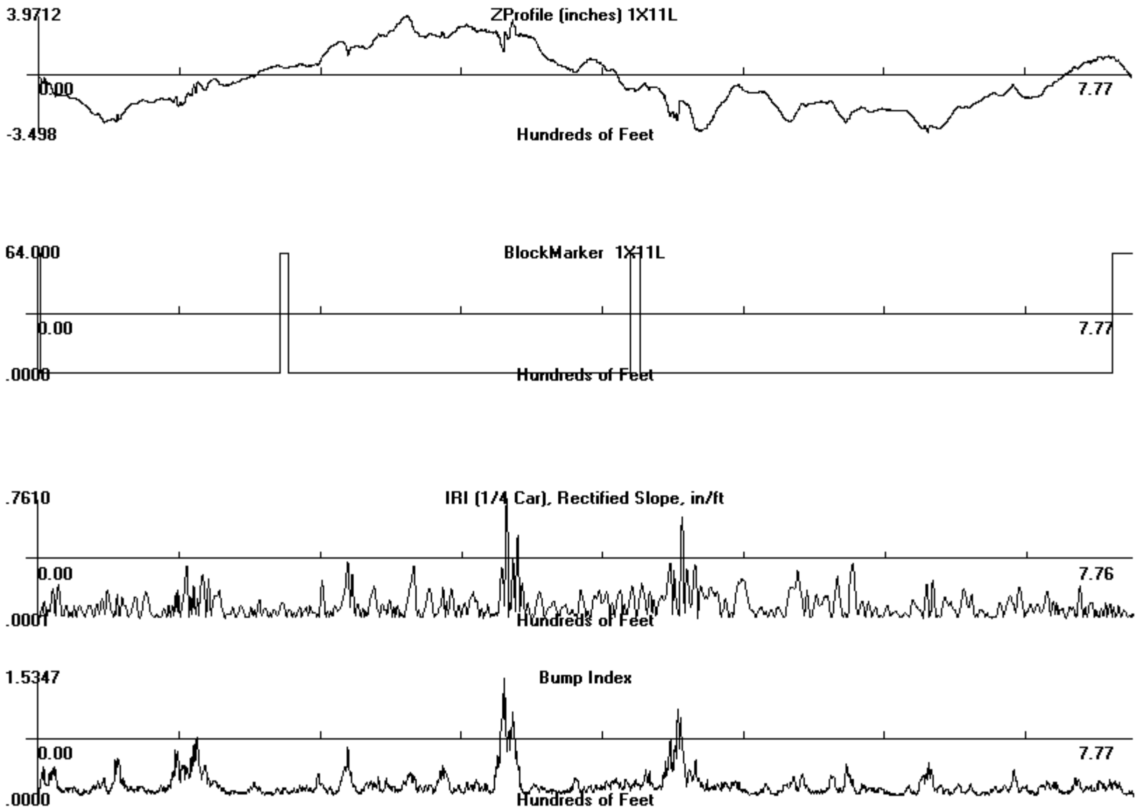


Table Indexes of cluster 1X11L

Block	Length(ft)	IRI(m/km)
1	171.4	5.9449
2	248.5	7.6564
3	356.8	7.4675
Total	776.7	7.1919

Table Bump Index 1X11L

Peak No.	Distance from Start(ft)	Bump Index	Reference height(in)	Bump Height(in)	Bump Length(in)	Edge Length(ft)
1	330.3	1.535	0.825	1.266	11.150	5.575
2	53.6	1.132	0.893	1.011	19.512	5.343
3	336.6	1.108	0.982	1.088	30.661	5.575
4	112.7	0.768	0.848	0.651	13.937	5.807

This bump index corresponds well with transients in the IRI quarter-car axle-body displacement and the earlier generated straightedge and the bandpass filter indexes. (See definition below.) A constraint to this index is that all peaks (major bumps) are separated by at least 6 feet.

Boeing considers bump index measurement of 1.0 and above to be potential causes of aircraft injury. Therefore, Galaxy Scientific produced information to the Fund about all bumps that measured below 1.0 and above. The Fund for the City of New York chose to report the more severe bumps and therefore in this report includes only those bumps that have an index of 1.5 and above. This decision was made to account for differences between airplane and automobile stress, and to reflect the fact that people in the focus groups said they expect some bumpiness in the city's streets but find severe bumps intolerable.

Band Pass Index (BPI). The Band Pass Index (BPI) was developed under National Cooperative Highway Research Program (NCHRP) funding. Like IRI, BPI is computed from a measured highway profile. First, the profile is filtered to remove wavelengths longer than 8 feet and shorter than 1 foot. Then the root mean square (RMS) of the filtered profile is computed to give the BPI.

IRI and BPI are both average values derived from a filtered version of the highway profile. They differ in that 1) the IRI is accumulated axle movement and BPI is RMS, and 2) the IRI includes longer wavelengths.

Note: The straightedge and bandpass filter indexes were initially considered as alternative to IRI. Once it was determined that IRI correlated best with driver perception, the straightedge and bandpass filter indexes were no longer required.

<u>Measuring Devices Used</u>

Galaxy Scientific Corporation uses a Class II inertial profiling device to conduct pavement roughness measurements (Figure 5). Short of manually using a rod and level (Class I), this is the best practical method in use today for measuring long distances. Specifications for Galaxy's profilometers exceed the requirements of American Standard Testing and Materials (ASTM) Test Method E-950, "Measuring the Longitudinal Profile of Vehicular Traveled Surfaces with an Inertial Profilometer." The profilometer has three major components: the laser, the accelerometer, and the non-contact speed sensor. The <u>laser</u> (Selcom) measures the deviation of the vehicle from the pavement surface. This unit has a spot size of 1 mm. The sampling rate is 32 kHz, which gives a sampling distance of 0.011 inch at a test speed of 20 mph. The <u>accelerometer</u> measures the car's vertical movement; it is measured so that it can be filtered out later to produce a profile of the street uncontaminated by the vehicle's response. This filtering creates the effect of the laser remaining stationary as the contour of the road passes under it. The accelerometer signal is also sampled at 32 kHz. The laser's data, tempered by the accelerometer, produce a representation of surface deviations in the form of a profile. The ends of the profiles are also forced to have the same elevation to provide a better representation of the surface deviations, ignoring the difference in elevation between the start and stop points. The 32 kHz profile is filtered and decimated to give a final sample spacing of approximately 1 inch. The <u>non-contact speed sensor</u> provides information on the speed of the vehicle. The distance is derived from the speed. For this configuration, the measurement speed is limited to a maximum of 38 mph and approximately five minutes of data recording per measure (16,600 ft).

Laptop computers in the test vehicle capture the data from the measuring devices. The data are then processed at Galaxy's offices to produce IRIs, bump indices and supporting data.

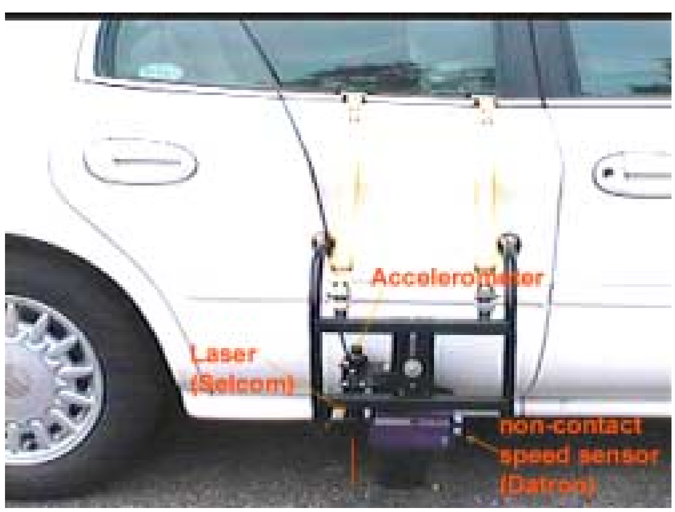


Figure 5. Galaxy Inertial Profiling Device Equipment Configuration

About Galaxy Scientific Corporation

Galaxy Scientific Corporation is a 10-year old high-technology company providing systems integration, engineering and other technical services and product development to the U.S. Departments of Transportation, Defense, Commerce, the Federal Aviation Administration, and commercial clients. Galaxy has offices in 14 cities in the United States, and one in Taiwan, Republic of China.

The Fund for the City of New York worked with Galaxy's Technology Group, engaging them to apply their tested equipment and processing to New York City's streets. Galaxy engineers and scientists are experts in highway and runway profile measurement and management, and the maintenance of airport pavements. Galaxy's staff of engineers and data processors has extensive experience in working with pavement measurement devices and analysis of profilometry data.

The Fund was also fortunate to benefit from the expertise of Dr. Gordon Hayhoe, currently with the Federal Aviation Administration (FAA). The FAA gave permission for Dr. Hayhoe to consult with the Fund on our city street measurement work. Dr. Hayhoe has had over 20 years of experience and participation in national and international research in the field of pavement testing and vehicle dynamics, and has authored some of the classical work on the topic. Dr. Hayhoe was working at Galaxy Scientific Corporation when our work began.

Preliminary Testing for This Project

The Fund for the City of New York asked Galaxy Scientific to conduct preliminary tests to demonstrate how reliable their profilometry devices are in replicating road roughness measures when driving different roads of varying roughness at varying speeds -- a condition required if accurate street surface measures are to take place in city traffic.

Under the direction of the Fund for the City of New York, Galaxy conducted roughness measurements on two secondary road segments to test/demonstrate repeatability and repeatability at different speeds. Two secondary roads were selected for this data collection effort because of their respective "very rough" and "smooth" characteristics. Descriptions of the two roads are as follows:

English Creek Road (Rough): This secondary road was selected because of its obviously rough surface, and poor ride quality. The road is 16 feet wide, paved with asphalt, and consists of numerous patches, cracks, small potholes, and wavy pavement as indicated in Figure 6. The representative section on this road was 841 feet long. Five runs were conducted along an intended identical path, attempting to capture the conditions of the pavement where vehicular traffic should travel (vehicle lane rather than "dodging" obvious bumps). Conditions during each of the passes were constant, with the only changes being the test vehicle's speed.

Figure 6. English Creek Road (Rough)

Individual data files for each run on the rough road were collected as follows:

Rough1 First run along the "rough" road, with the vehicle at approximately 23 mph.
Rough2 Second run along the "rough" road, with the vehicle at approximately 20 mph.
Rough3 Third run along the "rough" road, with the vehicle at approximately 25 mph.
Rough4 Fourth run along the "rough" road, with the vehicle at approximately 30 mph.
Rough5 Fifth run along the "rough" road, with the vehicle at a slower speed of 15 mph.

Access Road to Corporate Park (Smooth): This road was selected as a smooth sample because of its near perfect condition, and minimal exposure to traffic. The road is 25 feet wide, paved with asphalt, with no visual defects or flaws as indicated in Figure 7. The representative section was 765 feet long. Six runs were conducted along an intended identical path on this road, attempting to capture the portions of the pavement where vehicular traffic would travel (vehicle lane). Conditions during each of the six passes were constant, with the only changes being the test vehicle's speed.

Figure 7. Access Road to Corporate Park (Smooth)

Individual data files for each run on the smooth road were collected as follows:

Smooth1 First run along the "smooth" road, with the vehicle at approximately 25 mph.
Smooth2 Second run along the "smooth" road, with vehicle at approximately 22 mph.
Smooth3 Third run along the "smooth" road, with the vehicle at approximately 25 mph.
Smooth4 Fourth run along the "smooth" road, with the vehicle at approximately 25 mph.
Smooth5 Fifth run along the "smooth" road, with the vehicle at approximately 30 mph.
Smooth6 Sixth run along the "smooth" road, with the vehicle at a speed of 15 mph.

The results of the pilot tests are shown in Table 1.

Table 1. Pilot Test Results

Road Segment	IRI	BPI
Rough1	12.538	0.150
Rough2	12.441	0.152
Rough3	12.188	0.143
Rough4	12.524	0.145
Rough5	12.537	0.145
Smooth1	1.802	0.017
Smooth2	1.810	0.016
Smooth3	1.772	0.017
Smooth4	1.833	0.016
Smooth5	1.855	0.017
Smooth6	1.868	0.017

Since the testing resulted in similar measurement at varying speed on the same street, Galaxy Scientific was asked to conduct further trials on New York City streets and confirmed that reliable results could be obtained at the proposed study site.

The Fund for the City of New York also asked a social science research company (DYG, Inc.) to conduct a test to determine if there was a correlation between the objective measurements and the perceptions of typical New York City drivers. Several drivers were asked to evaluate the rideability of the same streets measured objectively by Galaxy. Galaxy performed a regression analysis of the two sets of data and, indeed, found a high degree of correlation. A comparison of the people's ratings to those of Galaxy Scientific's results is shown in Figures 8, 9 and 10. See Section II of the Technical Appendix for a further discussion of the purpose and use of the comparison.

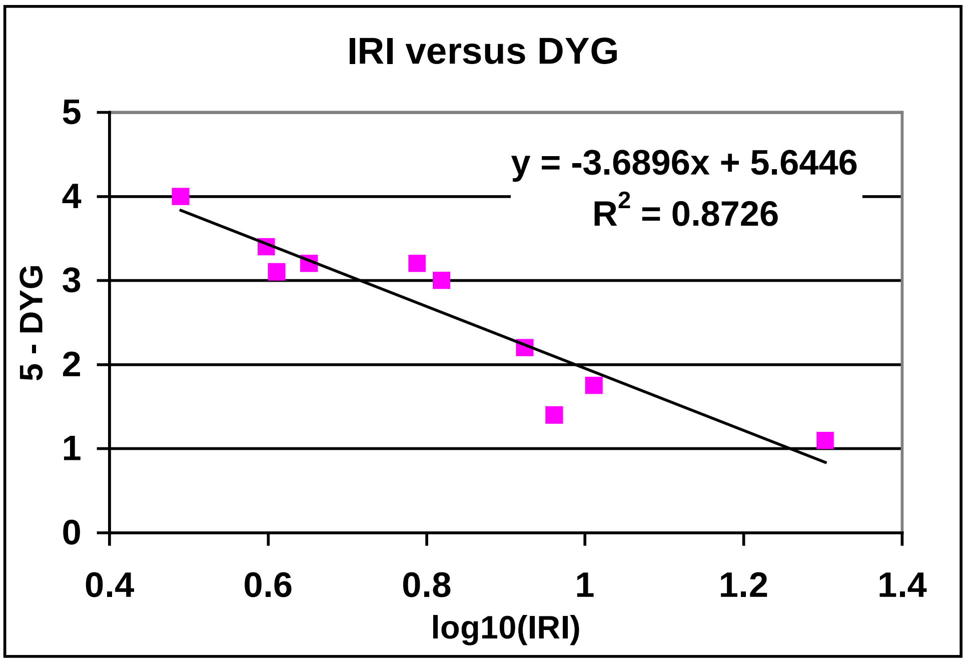


Figure 8. Comparison of IRI to People's Responses

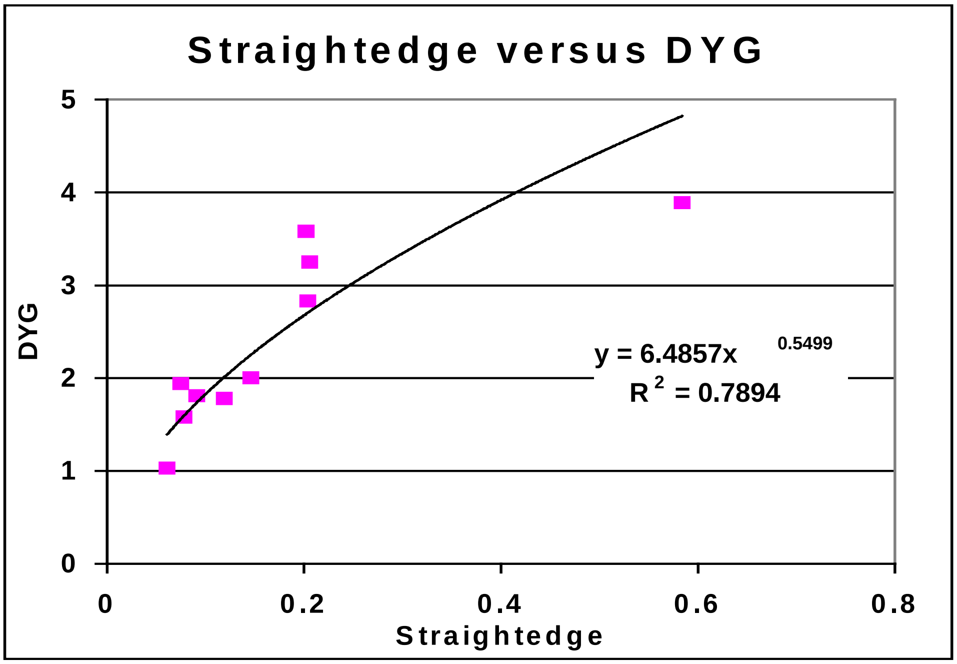


Figure 9. Comparison of Straightedge to People's Responses

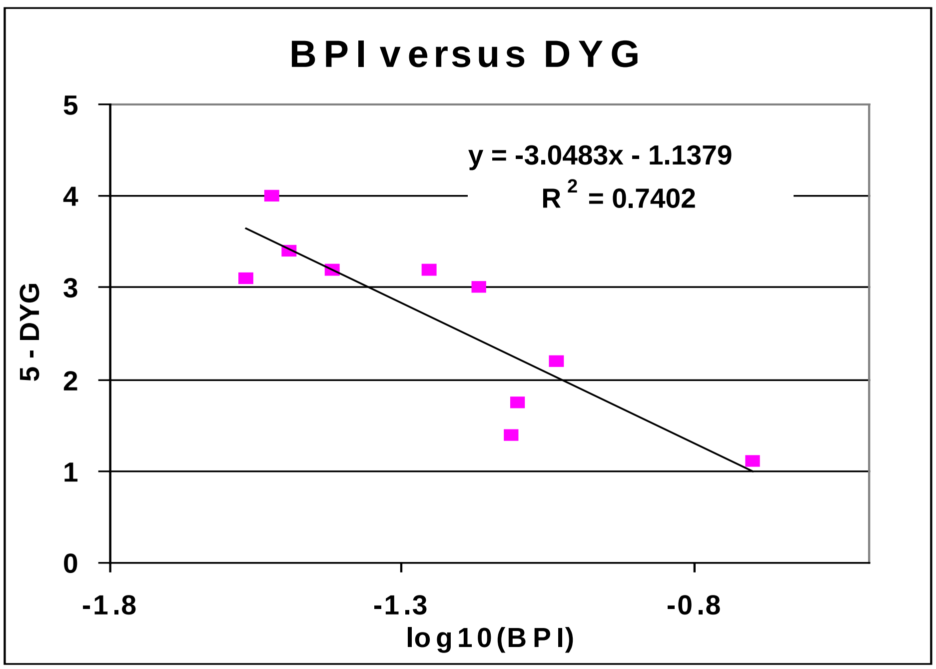


Figure 10. Comparison of Bandpass to People's Responses

The Citywide Survey: Data Collection

Data were collected in all five boroughs of New York City and in every Community District. The collection effort was conducted from 7 October through 18 November 1997 for approximately twelve hours (2 shifts) per day, six days per week. The equipment was serviced weekly (on the seventh day). The same vehicle, a 1997 Mercury Sable, and equipment as configured in Figure 11 were used for all measurements. A video camera mounted on the dashboard of the vehicle was also used to provide a pictorial of the road surface conditions for future analysis by the Fund. Drivers, navigators, and equipment operators were rotated on a regular basis. Standard operating procedures were in place throughout the data collection effort. Both left and right wheelpaths were measured. Because of the data collection schedule, on site examination of the collected data was not possible. At the end of each day, the collected data were compressed, tagged and sent via express mail to the Galaxy offices for examination and processing. Data from Staten Island, with its three districts, was collected first in order to obtain preliminary results for analysis of an entire borough early into the project. A total of 1,352 miles of data (left and right wheelpaths) for the five boroughs were collected.

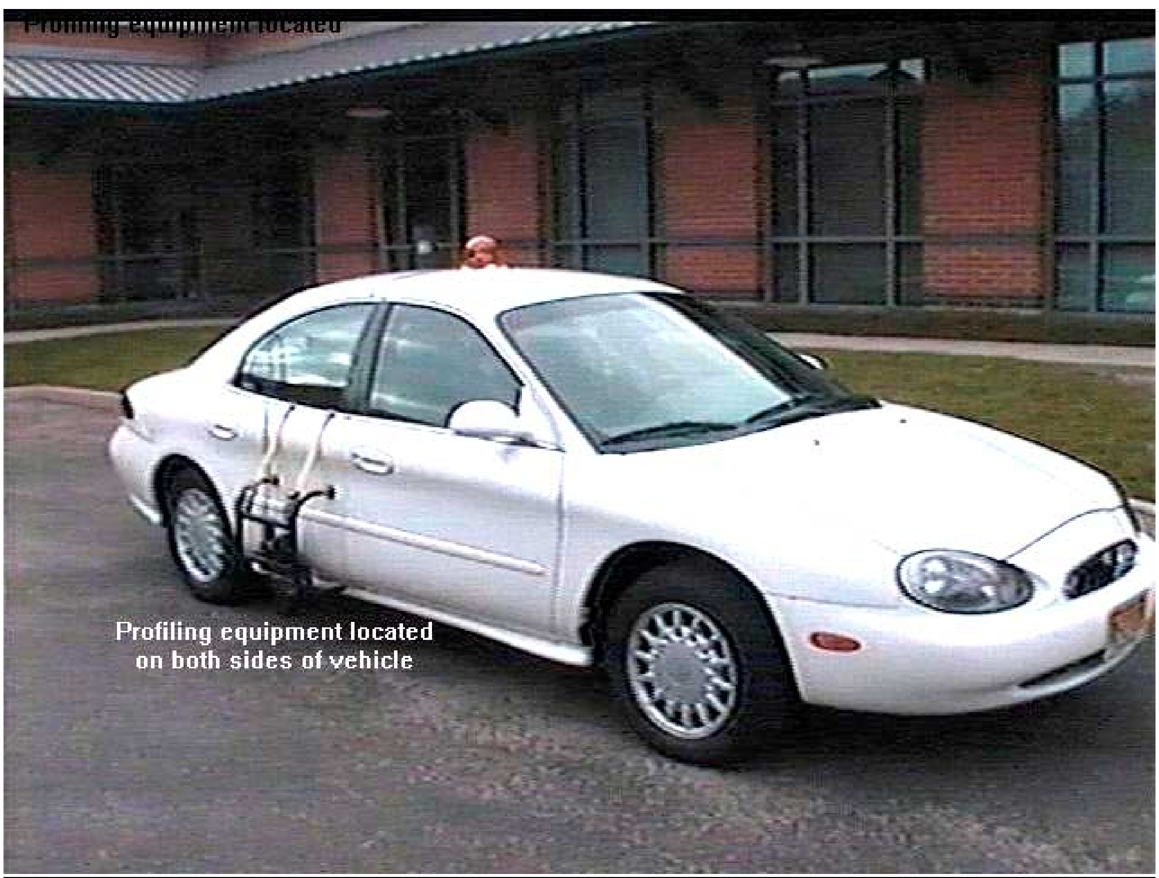


Figure 11. Data Collection Vehicle

The Citywide Survey: Data Processing

Upon receipt at the Galaxy offices, quality checks were performed. The raw data signals (accelerometer, speed, vertical displacement) were checked for anomalies which, if found, were relayed back to the data collection teams for corrective action. A document file was generated for each cluster that initially contained:

1. Plot of the cluster profile;
2. Plot of the vehicle speed;
3. Plot of the block marker;
4. Plot of the straightedge deviations;
5. Plot of IRI;
6. Plot of the bandpass filter index;
7. Plot of the California profilograph;
8. Plot of a probability distribution function; and a
9. Tabular form of the above indexes.

The Straightedge deviations, bandpass filter indexes and California Profilograph plots were used in the development of the bump index.

Further processing of the above outputs generated a spreadsheet, complied by district, containing:

1. Cluster and block lengths (combined left and right wheelpaths);
2. IRI for each block and cluster (combined left and right wheelpaths); and
3. Bump Indexes equal to or greater than 1.0 within the cluster (and the first bump index <1.0).[5]

Each row within the spreadsheet represented a cluster for length and IRI, and each cluster was represented by two rows (left and right wheelpaths) for Bump indexes.

IRI was computed using a direct implementation of the computer program listed in World Bank Technical Paper Number 46[6]. The sample spacing is 6 inches. Units are meters per kilometer (m/km). An IRI for each marked block within the measured cluster was calculated as the average of the IRI values for the left and right wheelpaths as:

$$\frac{IRI_{(left)} * L_{(left)} + IRI_{(right)} * L_{(right)}}{L_{(left)} + L_{(right)}}$$

where L = Length for the block; (left) and (right) signifies wheelpath.

[5] The Fund for the City of New York chose to report the more severe bumps and therefore in this report includes only those bumps that have a 1.5 index and above. This reflects the fact that people in the focus groups said they expect some bumpiness in the city's streets but find severe bumps intolerable.

[6] World Bank Technical Paper Number 46: Guidelines for Conducting and Calibrating Road Roughness Measurements, Sayers, M.W., Gillespie, T.D., Patterson, W.D.O.

The IRI for the cluster utilizes the same equation as above, substituting total cluster length for *L*.

Note: A maximum IRI limit for any single block was set at 20, which would account for any extreme roughness without skewing the data at the district level. Jolts created by riding over speed bumps that are designed to calm traffic were excluded from the City Roughness Index and from the Jolt Count.

Problems and Corrections

The data collection portion of this project was completed without any major incident. There were no traffic accidents, major equipment malfunctions or weather delays of more than three consecutive days.

In total, 4,850 cluster measurements were taken. Only 10 clusters, consisting of either a left or right wheelpaths, but not both, were unusable.

The most significant problem was due to the equipment's sensitivity to intense usage (12 to 14 hours a day, 6 days a week for 7 consecutive weeks) on a number of rough road surfaces which Galaxy had not anticipated. As a result, there were 10 occasions where there was a loss of accelerometer readings for either the left or the right wheelpaths:

District	**Problem**
Brooklyn 5	No left side accelerometer signal
Bronx 7	No right side accelerometer signal
Bronx 8	No right side accelerometer signal
Bronx 9	No right side accelerometer signal
Bronx 10	No right side accelerometer signal
Bronx 11	No right side accelerometer signal
Richmond 1	No right side accelerometer signal
Richmond 2	No right side accelerometer signal
Richmond 3	No right side accelerometer signal
Brooklyn 3	Weak left and right accelerometer signal

Galaxy substituted the working accelerometer signal to compute the IRI and bump index in these cases. The accelerometer signal in one district (Brooklyn 3) was too weak on both sides to be considered reliable. In this case, Galaxy examined accelerometer readings in three other similar districts and performed regression analysis to develop proxy accelerometer readings in this one district. It should be noted that the laser and speed sensor readings for Brooklyn 3 were reliable and thus utilized for the computation of IRI and bump index.

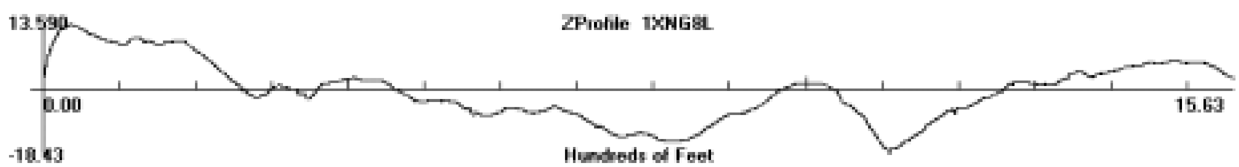
Blocks within a cluster were marked by injecting a foreign signal into the recording which could be detected during the data processing phase. In 63 instances, the block mark could not be detected from one wheelpath, and therefore, some block counts and lengths were determined from the data obtained from the opposite wheel path.

Some of the collected data files were misnamed but all conflicts were resolved by comparing records from the data collector notes and navigator logs.

Data Presentation

Galaxy computed profiles for 2,306 clusters of blocks measured. A total of 54 clusters were not measured because they either could not be found or were missed as a result of them being inaccessible or other various difficulties encountered in the field. The 25 clusters that could not be found represent 1.1% of the sample. The 29 clusters that were missed represent 1.2% of the sample.

The following indexes are illustrated for the profile cluster 1XNG8L. This profile is an example of the data for each cluster presented by Galaxy to the Fund. This particular profile has a number of well-defined depressions:



Peak values resulting in a bump index greater or equal to 1.0 (plus the highest value less than 1.0) were computed from the bump index record under the constraint that all peaks are separated by at least 6 feet. The results were tabulated and shown below (Table 2):

Table 2. Five Largest Peaks For Cluster 1XNG8L

Peak	Distance from Start (ft)	Bump Index	Bump Height (in)	Bump Length (ft)	Straightedge Length (ft)
1	1195.1	1.318	-1.206	0.915	5.807
2	1110.1	1.183	-1.082	1.858	5.807
3	562.8	1.167	-1.095	0.938	5.807
4	259.2	1.029	-0.872	1.161	3.252
5	2.1	0.917	0.839	0.915	5.807

Data Summary

Table 3 provides cluster and block statistics on the data collected for the New York City survey.

Table 3. Selected Sample Statistics

	Total Number of Community Districts	Total Length Sampled (mi)	Total Number of Clusters	Total Number of blocks	Block Length Maximum (mi)	Block Length Minimum (ft)	Block IRI (m/km)*** Maximum**	Block IRI (m/km)*** Minimum
New York City	59	676.24	2306*	6396				
Bronx	12	130.82	466	1673	1.21	51.74	26.67	1.57
Brooklyn	18	261.64	704	3257	0.59	50.69	30.63	1.51
Manhattan	12	102.8	472	1428	1.15	43.82	39.77	1.27
Queens	14	155.31	549	2106	0.99	50.16	24.5	1.31
Staten Island	3	25.67	115	391	0.45	50.16	21.56	2.2

*This number is 115 fewer than the 2421 clusters reported to the Fund by Galaxy Scientific. The difference was a result of Galaxy's need to divide some clusters into 2 or more sections because of a five-minute maximum recording time imposed by storage limitations of the laptop computer used for data collection. The Fund consolidated the sectioned clusters back into their original clusters.

**For analysis by the Fund for the City of New York, 20 was set as the maximum IRI limit for any single block. This established the limit for a worse case situation in order to prevent any unnecessary skewing of the overall data.

***IRI readings from the left or right side profilometer. For analysis by the Fund for the City of New York, the average of the left and right side profilometer IRI was used.

II. ASSIGNMENT OF CITY ROUGHNESS INDEX (CRI) CATEGORY BOUNDARIES

Consistent with the Fund's intention to obtain and present valid, objective measurements in a manner that reflects the public's perspective, the Fund used the public's perception of the quality of the city's streets to determine the scaling and categorizing of the objective data collected by Galaxy Scientific Corporation. In developing our approach, the Fund was informed by the panel rating method developed for use on high-speed highways.

The Fund asked DYG, Inc., the social research firm that conducted our original focus groups research in 1995, to design a methodology that would systematically capture the views of New York City drivers of New York City streets. DYG invited back some members of the original focus groups who had discussed the condition of the city's streets to become part of a panel of raters to drive over and then rate various clusters of street blocks in New York City. This test took place in July 1997 under the supervision of Madelyn Hochstein, President of DYG, Inc. and her staff and Dr. Martin Frankel, the Fund's statistical consultant for this project. Some Fund staff also participated in the test.

The panels rated road segments in New York City with varying degrees of roughness. Raters independently rated each cluster on a scale of 1 (best) to 4 (worst). Immediately after riding on and rating the selected street clusters, the participants were brought into a focus group discussion observed by Dr. Frankel and led by Ms. Hochstein. They were asked to talk in depth about the reasons for their ratings and the adequacy of the 1-4 scale. Even before the discussions there was considerable agreement in the ratings (see Table 4). Dr. Frankel and Ms. Hochstein observed from the comments of the focus group participants that typical drivers do consistently rate street roughness, that there was little variation on the raters' judgments, and that the four-point scale appeared to cover the major differences in street roughness that were of concern to these typical NYC drivers.

Table 4. Road Ratings Tally Sheet

	Rater 1	**Rater 2**	**Rater 3**	**Rater 4**	**Rater 5**	**Rater 6**	**Rater 7**	**Rater 8**	**Rater 9**
Segment 1	3	3	4	4	3	Almost 4	4	3	2.75
Segment 2	4	4	4+	4	4	4	4	3.5	3.5
Segment 3	2	1	1	2-3	1	1-2	1.5	1.75	Almost 2
Segment 4	2	1	1	2	2	2	1.5	2.25	2.25
Segment 5	2	1	2	2	2	1.75	2	1.75	1.75
Segment 6	3	2	3	3	3	3	2-3	3	3
Segment 7	3	1	2	3	1	1-2	2	2.25	1.5-1.75
Segment 8	2	1	2	2	2	2	2	2	2.5
Segment 9	4	3	3	3	3	3-4	3	3+	3.5-3.75
Segment 10	4	3	3	4	4	4	3.5	3	3.75
Segment 11	1	1	1	1	1	1	1	1.25	1

The following day, Galaxy Scientific Corporation measured the profiles of the same clusters rated by the survey participants. These profiles produced the International Roughness Index or IRI, later renamed as City Roughness Index (CRI). Galaxy's objective measurements were subsequently correlated with the people's ratings. As Figure 12 shows, there is a very high correlation (R^2=0.8726) between the people's ratings and the objective ratings for each cluster.[7]

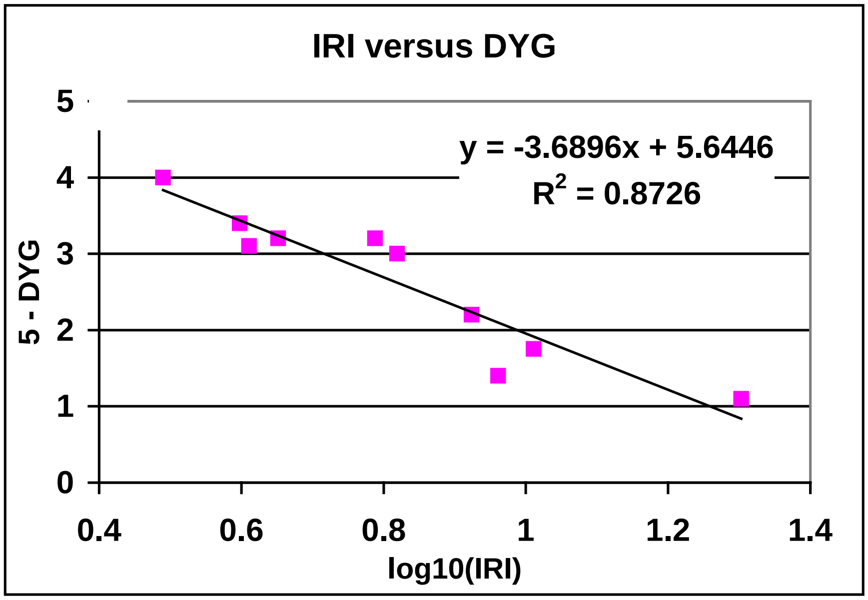


Figure 12. Correlation of People's Ratings (DYG) with the IRI (Galaxy)

This correlation provided the basis for assigning boundary values for each City Roughness Index (CRI) categories. In consultation with Dr. Frankel and following the principles of the "bell curve," the boundary values on the 1-4 scale were placed at 1.5, 2.5, and 3.5. In other words, the best category extends from a subjective rating of 1 to 1.5. The next best category extends from 1.5 to 2.5. The next to worst category extends from 2.5 to 3.5. The worst category extends from 3.5 to 4.

Using these boundary points of 1.5, 2.5 and 3.5 from the scale that the people used, the corresponding City Roughness Index (CRI) could be determined from the above correlation curve and formula. On this basis, the boundaries are calculated as shown in Table 5.

Table 5. 4-Point City Roughness Index (CRI) Scale

Scale	People's Description	People's Boundaries	CRI Boundaries
1	Good	1-1.5	3.81 or less
2	Fair	1.5-2.5	3.82-7.12
3	Poor	2.5-3.5	7.13-13.28
4	Terrible	3.5-4	13.29-20

[7] Galaxy Scientific did not include Segment 1 in the correlation calculation because the pothole that affected the rating of focus group participants was filled before Galaxy measured the same segment.

III. SAMPLING METHODOLOGY AND WEIGHTING PROCEDURE

Sampling Methodology

The sampling methodology was designed and implemented by Dr. Martin Frankel. Dr. Frankel has had a distinguished career in statistics and is the author of numerous articles and books on the use of statistics and sampling techniques. He is Professor of Statistics and Computer Information Systems and Deputy Chair of the Department at Baruch College of the City University of New York. He is a Fellow of the American Statistical Association and has chaired the Association's section on Survey Research Methods. Recently, Dr. Frankel developed statistical sampling procedures that are in use at the New York City Police Laboratory. Dr. Frankel received his B.A. in Mathematics from the University of North Carolina, an M.A. in Mathematical Statistics from the University of Michigan and a Ph.D. in Mathematical Sociology from the University of Michigan.

The overall objective of this project was to obtain valid and unbiased estimates of the smoothness of the city's streets for each of the 59 community districts in New York City. The basic objective of the sample design was to provide a subset of streets within each community district that would properly represent all of the streets that comprise each community district.

In order to assure that the sample representation of streets within each district would be both valid and objective, the sample selection was based on the principles of "Probability Sampling." Probability sampling is recognized as the only statistical method of sample selection that assures that sample results may be scientifically projected to the results that would be obtained from including the entire population.[8]

Probability sampling requires that each element that comprises the entire population have a "known, non-zero" chance or probability of selection into the sample. This basic principle was followed in the selection procedure used to obtain the samples of city streets from each community district. The implementation of the sampling process proceeded as follows:

STEP 1:

The Fund derived its sample of New York City's streets from the New York City Department of Transportation's (DOT) Street Smart database. The Street Smart database includes all the street blocks in each of the 59 community districts. An individual street block is defined as the shortest portion of a street or roadway that spans two intersections.

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[8] Kish, L, Survey Sampling, New York: John Wiley and Sons, Chapters 1-2, 1965.

According to the Street Smart database, there are a total of 75,766 blocks in New York City. For this survey, the Fund measured 8,855 blocks, which are almost 12% of New York City's blocks. As shown in Table 6, community districts vary considerably in terms of the number of blocks.

Table 6. Total Number of Blocks in New York City (Community District Distribution)

Community District	Bronx	Brooklyn	Manhattan	Queens	Staten Island	
1	745	1,730	554	1,363	3,337	
2	481	941	681	1,295	2,918	
3	521	925	562	1,032	3,682	
4	709	806	385	943		
5	542	1,826	662	1,987		
6	629	993	333	991		
7	597	1,006	661	3,060		
8	670	439	641	1,831		
9	1,107	462	456	1,628		
10	1,221	1,147	568	1,860		
11	1,197	1,399	446	2,638		
12	1,502	1,293	769	3,583		
13		762		3,968		
14		1,184		1,601		
15		1,882				
16		730				
17		1,385				
18		2,500				
TOTAL	**9,921**	**21,410**	**6,718**	**27,780**	**9,937**	**75,766**

STEP 2:

Each of the individual street blocks was linked into contiguous groupings known as primary sampling units (PSUs) or clusters. The creation of clusters followed a geographic ordering within each community district. Within each district, following this geographic ordering, PSUs numbered from 1 to N. Table 7 shows the number of PSUs (N) that were created in each district.

Table 7. Total Number of Clusters (Community District Distribution)

Community District	Bronx	Brooklyn	Manhattan	Queens	Staten Island	
1	177	280	185	392	993	
2	119	321	212	332	833	
3	128	155	189	293	994	
4	241	126	111	349		
5	125	273	193	602		
6	151	176	112	310		
7	154	165	171	823		
8	175	75	167	340		
9	185	96	140	323		
10	298	179	173	359		
11	236	292	130	588		
12	350	266	288	821		
13		184		733		
14		178		440		
15		313				
16		110				
17		217				
18		546				
TOTAL	**2,339**	**3,952**	**2,071**	**6,705**	**2,820**	**17,887**

The number of blocks assigned to a cluster was informed by research conducted for the Transportation Research Board and Federal Highway Administration in 1988 on subjective evaluation of road conditions in which the practice was to give raters at least 30 seconds driving duration in order to form an impression of the segment.[9] We wanted our objective rating to simulate a person's experience in the survey and therefore selected segments that would take at least 30 seconds to navigate. At 20 miles per hour, a reasonable driving speed on local streets, 30 seconds allows one to cover roughly 900 feet. Since a city block is about 250 feet long we picked four blocks as a convenient length for rating segments. In more suburban areas where driving speeds tend to be faster, we lengthened the cluster. At 30 miles per hour -- the legal speed limit in New York City unless posted otherwise, one would need to travel a quarter of a mile or 1320 feet to meet the 30 seconds minimum standard.

Generally, the clusters in the sample consisted of 4-6 blocks in dense areas and 6-10 blocks in less dense areas (e.g. parts of Staten Island). Adhering strictly to these lengths is not possible. In some places, streets are only one block long. In other places, a convenient and meaningful stretch of road might cover more than 4 to 6 blocks. Nevertheless, on average, the city has been divided into 17,898 clusters which average 4.45 blocks long.

[9] Janoff, Michael S.,"NCHRP Report 308: Pavement Roughness & Rideability Field Evaluation", Transportation Research Board: USA, July, 1988.
Janoff, Michael, S., "Pavement Roughness and Rideability Field Evaluation", Transportation Research Board: USA, August, 1988.

STEP 3:

The Fund provided Dr. Martin Frankel with a list of the number of clusters in each community district. Dr. Frankel, in turn, provided the Fund with 40 randomly generated numbers within the range of cluster numbers for each community district. In other words, Dr. Frankel identified 2360 clusters -- 40 clusters from each of the city's 59 community districts.

Systematic random sampling was used to obtain a sample of 40 clusters within each community district. Systematic random sampling was used because it assures that each PSU (cluster) and each individual block, as well, is given an equal probability of selection and it assures implicit geographic stratification of the resulting sample.[10]

STEP 4:

Driving Direction

The preferred driving direction for each cluster was randomly assigned by flipping a coin to determine the direction for the first cluster in each district (A to B or B to A) and then alternating successively numbered clusters in the district. Of course, the preferred direction was respected unless it was contrary to the one-way designation of the street in which case the one-way requirement took precedence.

Lane Selection

The preferred lane in which to travel while measuring was also randomly assigned by flipping a coin to determine the preferred lane (left or right) for the first cluster in each district and then alternating lanes in the remaining clusters in the district. A lane was defined based on the presence of lines on the street offering more than one lane in the direction of travel. When a street turned out to have more than two lanes, a further random assignment was made on the spot by further coin flips. Of course, traffic conditions such as double parking, traffic jams and other impediments such as fuel deliveries made it impractical to honor completely the lane preference. Streets with no marked lane, regardless of width, were considered to be single-laned.

[10] Kish, L, Survey Sampling, New York: John Wiley and Sons, Chapters 4, 1965.

Weighting Procedure

Dr. Martin Frankel advised that because of the considerable variation in the length of New York City block segments (the distance on a street between two successive crossing streets), statistics describing the percent of “acceptable” blocks should be computed on a weighted basis. This means that longer than average block segments have relatively greater impact on the overall percentage of acceptable blocks while shorter than average blocks have relatively less impact. For example, suppose a district consisted of only three block segments of lengths 300 feet, 300 feet, and 400 feet respectively. Also suppose that the first block (length 300 feet and the third block (length 400 feet) were classified as acceptable, while the second block was classified as not-acceptable. The proportion of acceptable blocks on a feet “WEIGHTED” basis would be 70% (= 700/1000, since the total length of acceptable blocks is 300+400 =700, relative to a total length of 300+300+400=1000). If the proportion of acceptable block were calculated on an “UNWEIGHTED” basis, it would be 66.6% (= 2/3 blocks). Since a car moving at a constant speed will spend more time on a longer street segment, it was felt that the use of weighted proportions would more correctly correspond to the length of time a person in a car would be experiencing an “acceptable” ride.

The data on Jolts Encountered Per Mile is simply the total number of bumps divided by the miles of street sampled. This ratio is comparable from district to district, and requires no weighting procedure.

IV. ESTIMATION AND COMPUTATION OF STANDARD ERRORS[11]

The Basic Estimates (Percent of blocks acceptable and Number of Jolts Encountered Per Mile) are statistically described as "Ratio" estimates of the form

$$R = \frac{\sum_{h=1}^{H} \sum_{i=1}^{n_h} Y_{hi}}{\sum_{h=1}^{H} \sum_{i=1}^{n_h} X_{hi}}$$

In this formula, H denotes the number of Community Districts included in the particular estimates. For various estimates, H may range from 1, for a single community district, to 59, for the entire city. The lower case letter h is used as the corresponding index for H.

The subscripted letter n_h denotes the sample size (in terms of selected PSUs or clusters) within the h^{th} district. In general n_h was 40, but in some instances the number was less than 40, because streets were either closed, non-existent or other wise not measured.

The probability of selection applied to all PSUs (clusters) within the h^{th} community district (with appropriate non-observation compensation) is denoted as f_h. The values of Y_{hi} and X_{hi} are defined as follows:

For both the percent of blocks acceptable and the number of jolts per mile, the value X'_{hi} is defined as the number of measured feet in the i^{th} selected PSU of the h^{th} community district. Then, the probability weighted value X_{hi} , is defined as $X_{hi} = X'_{hi} / f_h$.

For the estimate of the percent of blocks acceptable we define Y_{hi} as total number of measured feet in the "acceptable" blocks within the i^{th} selected PSU of the h^{th} community. This value was multiplied by 100, to convert a proportion to a percentage. For the number of jolts per mile, we define Y_{hi} as the total number of jolts recorded in the i^{th} selected PSU of the h^{th} community divided by the constant 5,280. This constant is included so that the estimate is re-scaled from jolts per feet to jolts per mile.

Then, the probability weighted value Y_{hi} , is defined as $Y_{hi} = Y'_{hi} / f_h$.

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[11] This section was prepared by Dr. Martin Frankel.

The standard error of R, se(R) is estimated by se(R).

$$se(R) = \left[\frac{1}{X^2} [\sum_{h=1}^{H} \text{var}(y_h) + R^2 \text{var}(x_h) - 2R\,\text{cov}(y_h, x_h) \right]^{1/2},$$

where

$$X = \sum_{h=1}^{H} \sum_{i=1}^{n_h} X_{hi},$$

$$X_h = \sum_{i=1}^{n_h} X_{hi},$$

$$Y_h = \sum_{i=1}^{n_h} Y_{hi},$$

$$\text{var}(y_h) = \frac{1-f_h}{n_h - 1} \left(n_h \sum_{i=1}^{n_h} Y_{hi}^2 - Y_h^2 \right)$$

$$\text{var}(x_h) = \frac{1-f_h}{n_h - 1} \left(n_h \sum_{i=1}^{n_h} X_{hi}^2 - X_h^2 \right)$$

$$\text{cov}(x_h y_h) = \frac{1-f_h}{n_h - 1} \left(n_h \sum_{i=1}^{n_h} XY_{hi} - X_h Y_h \right)$$

The limits shown in Table 8 are equal to the estimate R, plus and minus 1.64 times the estimated standard error of R. This produces a 90% confidence interval range.

Selected findings from the survey are shown in Table 8 along with its 90% confidence interval range.

Table 8. Selected Survey Findings and Confidence Interval Ranges

			90% Confidence Interval	
		Findings	**Low**	**High**
New York City	% of Blocks Rated Acceptable	59.52%	58.22%	60.82%
	Number of Jolts Encountered Per Mile	9.49	9.13	9.85
Bronx	% of Blocks Rated Acceptable	58.49%	55.39%	61.59%
	Number of Jolts Encountered Per Mile	8.69	7.94	9.44
Brooklyn	% of Blocks Rated Acceptable	63.14%	61.11%	65.17%
	Number of Jolts Encountered Per Mile	8.39	7.86	8.93
Manhattan	% of Blocks Rated Acceptable	44.97%	42.02%	47.92%
	Number of Jolts Encountered Per Mile	14.18	13.08	15.27
Queens	% of Blocks Rated Acceptable	64.48%	61.69%	67.27%
	Number of Jolts Encountered Per Mile	9.25	8.47	10.03
Staten Island	% of Blocks Rated Acceptable	56.25%	48.39%	64.11%
	Number of Jolts Encountered Per Mile	7.52	5.8	9.24
Brooklyn 18	% of Blocks Rated Acceptable	83.95%	78.84%	89.06%
Manhattan 1	% of Blocks Rated Acceptable	24.16%	13.35%	34.97%
	Number of Jolts Encountered Per Mile	32.27	22.76	41.79
Brooklyn 11	Number of Jolts Encountered Per Mile	4.03	2.96	5.11