RED BUS LANE TREATMENT EVALUATION

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February, 2012

ABSTRACT

Since 2008, the New York City Department of Transportation (NYCDOT) has implemented red-colored bus lanes as part of its collaborative Bus Rapid Transit (BRT) program with MTA New York City Transit (NYCT). NYCDOT and NYCT have found that the red treatment is effective at reducing unauthorized bus lane usage. NYCDOT is seeking to improve the durability and cost-effectiveness of its preferred red lane treatment and, in 2010, began a research study to identify high performance red lane products and installation processes for different roadway surfaces. This paper presents the methodologies and findings from a series of field and laboratory tests used to evaluate red bus lane treatments for NYCDOT. The field evaluations included long-term observations of various products used on bus-only lanes, as well as durability and skid resistance testing. Parallel laboratory evaluations were undertaken to assess product durability and skid resistance in a controlled, indoor laboratory. The results indicate that a red epoxy-based street paint, an epoxy with red aggregate product, and a red asphalt concrete-based micro surface performed well across all field and laboratory tests.

INTRODUCTION

Since 2008, the New York City Department of Transportation (NYCDOT) has implemented red-colored bus lanes as part of its collaborative Bus Rapid Transit (BRT) program with MTA New York City Transit (NYCT). The program includes five pilot BRT routes across the city, three of which – the Bx12 Select Bus Service (SBS) on 207th Street in Manhattan and Fordham Road and Pelham Parkway in the Bronx, the M15 SBS on First and Second avenue in Manhattan, and the M34/M34A SBS on 34th Street in Manhattan – are currently in operation. These three SBS routes, as well as other major bus corridors have been outfitted with red bus lanes. An example of a red bus lane is shown in Figure 1.

NYCDOT and NYCT have found that the red treatment is effective at reducing unauthorized bus lane usage, including illegal parking and illegal driving in the bus lane. With fewer blockages in bus lanes, bus service is faster and more reliable. Based on NYCDOT research and observation, the red treatment provides the benefit of better bus service without negative impacts on traffic operations and safety. As a result, NYCDOT plans to include the red treatment as part of up-coming BRT and bus priority projects on Nostrand and Rogers Avenues in Brooklyn, downtown Jamaica in Queens, 34th Street in Manhattan, and Hylan Boulevard in Staten Island.

Figure 1. Example of a Red Bus Lane on First Avenue in Midtown Manhattan

When NYCDOT began considering red bus lanes as part of the BRT program, the agency sought to identify a red lane product that met the following criteria:

- High visibility: the product provided a clear visual signal to drivers;
- Durability: the product would last at least three years in a good to fair condition;
- Safety: the product provided adequate skid resistance for vehicles;
- Low cost: the product had a low installation cost;
- Ease of installation: product installation was technically feasible within an urban environment and did not require prolonged lane closure; and
- Ease of patching: the product color and look could easily be matched by utility companies that were repaving utility cuts.

Based on an informal review and evaluation of available products, NYCDOT decided to use an epoxy-based street paint for its initial red lane applications. The results have been mixed. On new asphalt surfaces the product has proven to be a durable red lane solution. On other surfaces, including concrete and older asphalt, the durability of the red lane product has been poor. The agency's experimentation with a Portland cement-based micro-surface on the concrete section of First Avenue in Manhattan also produced disappointing results.

NYCDOT was seeking to improve the durability and cost-effectiveness of its preferred red lane treatment and, in 2010, began a research study to identify high performance red lane products and installation processes for different roadway surface types, including existing asphalt, new asphalt, existing concrete, and new concrete. For this study, NYCDOT partnered with the

Thomas D. Larson Pennsylvania Transportation Institute (PTI) at the Pennsylvania State University. NYCDOT and PTI were interested in evaluating several different types of products, including:

- street paints
- epoxy and aggregate products (often sold as anti-skid coatings)
- asphalt concrete-based micro surfaces
- Portland Cement-based micro surfaces

The purpose of the study was not to identify one product for all surface types, but rather to identify the best product and process for each type of surface condition that NYCDOT encounters in New York City.

In April 2010, NYCDOT issued a Request for Information (RFI) to manufacturers of red lane products in an effort to identify potential red lane products and application processes that might be right for New York City. For each product, the RFI requested specifications, installation guidelines, and cost and durability data. The RFI was targeted broadly, seeking to identify product types and processes for each road surface type that is common in New York City, including existing asphalt, new asphalt, existing concrete, and new concrete. NYCDOT received eight responses. Based on the RFI and additional market research, DOT selected nine products from seven different manufacturers for lab and field testing. A full list of products tested is presented in the Table 1. Not all products underwent both lab and field testing.

Table 1. Red Bus Lane Products Tested

Product ID	Product Type	Field Test	Lab Test
1	Red Street Paint, Brand A	No	Yes
2	Red Street Paint, Brand B	Yes	Yes
3	Epoxy with Red Aggregate (anti-skid), Brand B	Yes	No
4	Epoxy with Red Aggregate (anti-skid), Brand C	Yes	Yes
5	Red MMA with Aggregate (anti-skid), Brand D	Yes	Yes
6	Red-Tinted Portland Cement Micro Surface, Brand E	Yes	Yes
7	Red-Tinted Portland Cement Micro Surface, Brand F	Yes	Yes
8	Red Asphalt Concrete Micro Surface, Brand G	Yes	Yes
9	Chip Seal with Red Binder, Brand G	Yes	No

This paper describes the lessons learned from NYCDOT’s previous red bus lane applications. It also describes the results of field and laboratory tests that were undertaken to evaluate the red bus lane treatments listed in Table 1. Product durability and skid resistance were assessed in the field, and similar tests were performed in the laboratory after the products were subjected to simulated traffic wear.

NYCDOT EXPERIENCE WITH RED BUS LANE TREATMENTS

NYCDOT has installed red bus lanes on a variety of surface types across New York's five boroughs. Table 2 provides an overview of the major red bus lane applications undertaken by NYCDOT since 2007. For most red lane projects, NYCDOT used an epoxy-based street paint (Product ID #1 in Table 1). In one case, NYCDOT used a Portland cement-based micro surface (Product ID #6 in Table 1).

Table 2. NYCDOT Red Bus Lane Applications

Location	Year of Application	Product	Surface and Pre-treatment
57th Street	2007 (removed 2009)	Product ID #1 (Street paint)	existing asphalt air blown/swept
Fordham Road/West 207th Street	2008 and 2009		existing asphalt/concrete air blown/swept
34th Street	2008		new asphalt air blown/swept
Willis Avenue			new asphalt/existing concrete air blown/swept
Livingston Street	2010		new asphalt air blown/swept
First/Second Avenue (asphalt section)			mostly new asphalt air blown/swept
First Avenue (concrete section)		Product ID #6 (micro surface)	existing concrete power washed/swept
Grand Army Plaza	2011	Product ID #1 (Street paint)	new asphalt air blown/swept

This section discusses the lessons NYCDOT has learned through its five years of experience with red bus lanes based on qualitative assessments by NYCDOT staff. The durability of the red treatment is examined by surface type, which NYCDOT has found to be one of the primary factors in determining red treatment performance.

Performance of Red Paint Treatments on Asphalt Concrete Roadways

NYCDOT has extensive experience with applying Product ID #1, marketed as high durability epoxy-based street paint, to asphalt concrete (AC) surfaces. The durability of this product has varied widely depending upon the age and condition of the underlying AC roadway. Overall, NYCDOT has found that Product ID #1 exhibits satisfactory durability when applied to new AC surfaces. Figure 2 shows the condition of a section of Product ID #1 red bus lane on First Avenue between 15th and 16th streets after one year of wear. At this location, the red treatment was applied to newly paved asphalt. As shown in the photo, the red treatment exhibits little chipping, peeling, or fading and is an effective traffic control device. The red treatment does exhibit some minor staining and marking. Similar durability results were found at other locations where Product ID #1 was applied to freshly laid AC streets.

Figure 2. Product ID #1 at First Avenue between 15**th** and 16**th** Streets

In contrast, NYCDOT has found that Product ID #1 exhibits unsatisfactory durability when applied to existing asphalt, particularly AC roadways in fair to poor condition. Figure 3 shows the condition of a section of Product ID #1 red bus lane on First Avenue between 14th and 15th streets after one year of wear. This section of red bus lane is contiguous with the section shown in Figure 2, and is subject to the same general level of wear by bus and vehicular traffic. This section of red treatment was applied to an AC roadway that was more than five years old. As shown in the photo, the red treatment exhibits significant chipping, peeling, and fading and is therefore less effective as a traffic control device. Similar durability results were found at other locations where Product ID #1 was applied to older AC streets.

Figure 3. Product ID #1 First Avenue between 14th and 15th Streets

In both of the above cases, the red treatment was installed with minimal surface preparation—installation crews simply swept or used compressed air to clear the roadway before application. One possible explanation for the discrepancy in durability is that accumulated oils, dirt, and other debris on the surface of older asphalt roadways hinders street paint adhesion, while the relatively clean surface of a new AC surface provides a more solid base. Surface cracking in older AC roadway surfaces, as shown in Figure 3, may also contribute to poor durability of products like Product ID #1 on these types of surfaces.

Regardless of the age and condition of the AC roadway surface, red treatments are exposed to particularly intense wear at bus stops, where the red treatment is subjected to the friction caused by buses stopping and starting and to prolonged heat exposure from bus engines. Figure 4 shows the condition of the red treatment at a bus stop on 34th Street at Second Avenue after three years of wear. While the non-bus stop sections of the red treatment on 34th Street are typically in satisfactory condition, the bus stop sections have exhibited significant wear, particularly in the wheel tracks. Similar results were found at most bus stops along the 34th Street corridor.

Figure 4. Product ID #1 Wear at a Bus Stop at 34th Street at Second Avenue

Conclusions

Based on the above qualitative evaluation of NYCDOT’s experience applying Product ID #1 to AC roadway surfaces, the study concludes that:

- Red paint products applied to new asphalt are projected to last about five years without failing (defined as loss of 50 percent coverage or more).
- Red paint products applied to existing fair to poor condition asphalt typically fails in less than one year.
- Red paint products wear faster at bus stop locations as compared to non-bus stop locations, likely due to the stopping and starting of buses and prolonged heat exposure from bus engines.
- Red paint products applied to new asphalt at bus stops will likely fail in two to three years.

Performance of Red Treatments on Concrete (Portland Cement) Roadways

NYCDOT has experience applying Product ID #1 and Product ID #6 to concrete (Portland cement) roadways. Both products have exhibited poor durability when applied to existing concrete surfaces.

Figure 5. Product ID #1 on concrete roadway in the vicinity of Sedgwick Avenue on Fordham Road after one year (left), red treatment concrete roadway at West 207th Street at Tenth Avenue after one year (right)

Figure 5 shows the condition of red bus lane sections treated with Product ID #1 on concrete roadways along Fordham Road in the Bronx and along 207th Street in Manhattan. After one year, these sections of red treatment exhibited significant chipping and peeling. In both cases, the red treatment was applied to existing concrete roadways that were more than five years old with minimal pre-treatment. The polished surfaces of these concrete roadways may have hindered the adherence of the red treatment.

In response to the problems encountered on Fordham Road, NYCDOT experimented with an alternate red treatment on the concrete section of First Avenue (installed as part of the M15 SBS project). NYCDOT used Product ID #6, a Portland cement-based micro surface, instead of a street paint product. Figure 6 shows the condition of the Product ID #6 section of First Avenue after nine months. As shown in the photos, this section of red treatment exhibited extensive chipping and peeling indicating that the product is not effective on existing concrete surfaces.

Figure 6. Product ID #6 applied to First Avenue between 88th and 89th Streets after Nine Months

Conclusions

Based on the qualitative evaluation of NYCDOT's experience applying Product ID #1 and Product ID #6 to existing concrete roadways, the study concludes that:

- Red-paint products applied to existing concrete surfaces will fail in six months to one year.
- Portland cement-based micro surfaces applied to existing concrete roadways will fail in six months to one year.
- Existing concrete roadways present a particularly difficult challenge when applying a red treatment for a bus lane.

FIELD TESTING

This section describes the results of field testing performed on eight red bus lane treatments along Third Avenue, between 36th and 42nd streets in New York City. The first series of field observations were performed in October 2010, less than two weeks after the products were applied on the paved asphalt bus lane. A second series of field observations were performed in April 2011 after each treatment experienced a period of winter weather and approximately six months of bus traffic. The project team used two quantitative procedures to assess the durability and skid resistance of each treatment.

Testing Site and Product Installation

Each participating manufacturer was assigned an 11-foot by 90-foot test patch on a section of a heavily used bus lane along Third Avenue in Manhattan. The asphalt in this section was three years old at the time of product application. Table 3 lists the product description, pre-treatment applied (if any) and the method used to apply the product. Some manufacturers opted to subdivide their test patches and apply two products. The products varied widely, ranging from three-part paints with an antiskid additive to micro surfacing products. Surface pre-treatment also varied widely, ranging from no pre-treatment to shot blasting or power washing the existing pavement surface.

Table 3. Red bus lane products, pre-treatment and application methods

Product ID	Product Type	Pre-Treatment	Application Method
2	Red Street Paint, Brand B	shot blasted pavement surface and existing markings, then cleared debris with blower	applied two coats using paint rollers
3	Epoxy with Red Aggregate (anti-skid), Brand B		base poured and manually evened; aggregate manually spread
4	Epoxy with Red Aggregate (anti-skid), Brand C	none	base poured and manually evened; aggregate manually spread
5	Red MMA with Aggregate (anti-skid), Brand D	shot-blasted pavement surface and existing markings, then cleared debris with blower	base coating sprayed on; aggregate manually spread
6	Red-Tinted Portland Cement Micro Surface, Brand E	power wash pavement and scarify existing markings	poured by truck and manually evened
7	Red-Tinted Portland Cement Micro Surface, Brand F	broom swept pavement	poured by truck and manually evened
8	Red Asphalt Concrete Micro Surface, Brand G	none	poured and manually evened; aggregate manually spread
9	Chip Seal with Red Binder, Brand G		base same as above; top layer machine applied

Field Testing Methods

This section of the paper describes the process used to evaluate the durability and friction of the red bus lane treatments applied in the field. All analyses were performed during two separate visits to the Third Avenue test locations – the first period immediately after the red bus lane products were applied and the second evaluation period approximately six months later.

Durability Testing using Digital Image Processing Methods

Digital image processing, which involves capturing two-dimensional, static images of each red bus lane treatment section, was used to assess the durability of each product. All digital images of the red bus lane treatments were captured using a Nikon D80 digital camera with a Nikkor 105 mm lens. A standard light and camera stand set at five feet, six inches above the roadway surface using a vehicle mounted frame holding the camera and the light fixtures was used to ensure strictly uniform digital imaging conditions.

Each manufacturer was provided a 90-feet long and 11-feet wide test section to apply their products. For each red bus lane treatment section, the research team positioned an 11-foot square rope to define the boundary conditions for the digital image processing. When only a single product was applied to the entire test section, eight digital images were recorded and processed. When manufacturers elected to subdivide their test section in order to test two products, four digital images were recorded and processed for each product in the test section. The first data collection period occurred in October 2010 when the treatments were less than two weeks old. A second data collection period occurred in April 2011, after a period of traffic wear and weathering.

The two-dimensional digital images were then processed using a software package developed by the research team for the purposes of this project. The computer code for the software program was written using Matlab®. The research team developed a series of algorithms to estimate the percentage of the surface area covered (i.e., durability) by the red bus lane treatments. The durability algorithm involves the following process:

- The images were standardized using a two-dimensional bi-cubic spatial transformation to remove lens distortions and deviations from standard projections from the image introduced by the distance and angle of the camera from the surface test area.
- The images were re-sampled using a bi-cubic pixel interpolation technique to transform all images to the same standardized digital grid size of 512 by 512 pixels.
- The images were subjected to a luminosity transformation with a morphological background light estimation technique to remove the effects of varying light conditions on the image.
- A clustering algorithm was applied to identify the surface area that was covered with a predefined color (red for bus lane treatments and white for symbol pavement markings). These predefined colors were then separated from the remainder of the image surface. This entire process involved the application of a two-phase iterative

- algorithm to minimize the sum of point-to-point centroid distances, summed over all existing different mean clusters using the "K-mean" algorithm.
- Batch updates were used to converge on a local minimum, representing the located optimal segmenting of the image points into areas covered with the predefined colors.

Friction Testing

A dynamic friction (DF) tester with a circular texture meter was used to evaluate the skid resistance of each of the red bus lane treatments. All testing was performed in accordance with ASTM E1911-09a, *Standard Test Method for Measuring Pavement Surface Frictional Properties Using the Dynamic Friction Tester* (Ref. 1). The DF tester measures the necessary torque to turn three small rubber pads in a circular path on the measured surface at different speeds. The required torque is then used to calculate the friction as a function of speed. Typical test speeds range from 3 mi/hr (5 km/hr) to 55 mi/hr (90 km/hr) . The DF tester is shown in Figure 7.

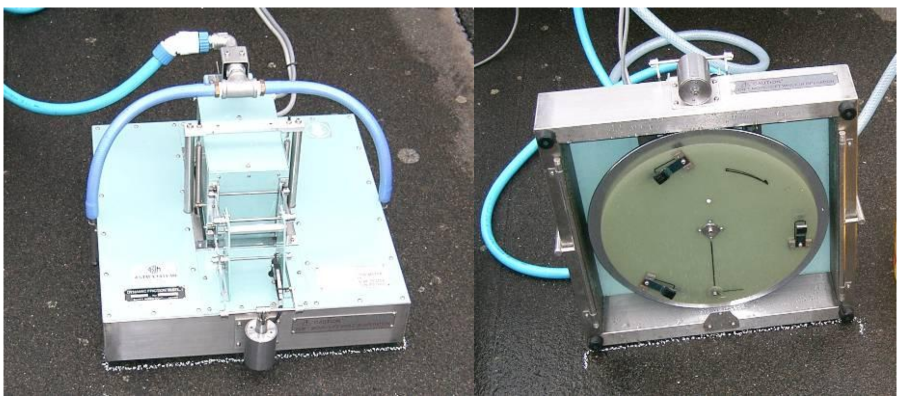


Figure 7. Dynamic Friction Tester

A circular texture (CT) meter was used in concert with DF tester to measure road surface texture characteristics. This device is designed to measure surface texture on the same circular track as the DF tester. The CT meter calculates and reports the mean profile depth (MPD) of the road surface and the International Friction Index (IFI).

Dynamic friction tests were completed at three locations within each treatment section in October 2010 and in April 2011. The three measurement locations included the left and right wheel paths of the bus lane and in the center of the lane. The friction measurements are provided in the analysis results section of this report.

Field Testing Results

Durability

Table 4 shows the results of the durability analysis. For each product, a digital photograph of the October 2010 field condition is shown next to a digital photograph of the April 2011 field condition. The percent coverage during the April 2011 period is shown in Table 4 along with the percent difference in surface coverage between the October 2010 and April 2011 periods. The percent reduction in the area covered by each red bus lane treatment was computed using the following equation:

$$\Delta Coverage = \frac{Avg.\%_{October\,2010} - Avg.\%_{April\,2011}}{Avg.\%_{October\,2010}} \times 100 \qquad (1)$$

where:

- $\Delta Coverage$ = percent reduction in the area covered by the red bus lane treatment between the period in October 2010 and April 2011.
- $Avg.\%_{October2010}$ = average percent area covered by red bus lane treatment in October 2010
- $Avg.\%_{April2011}$ = average percent area covered by red bus lane treatment in April 2011.

Based on the durability results, two products (product ID #5 and #6) did not experience any loss of coverage after a period of six months of traffic wear and weathering. Product ID #6, however, did show evidence of cracking. Upon further visual inspection after nine months of wear and weathering, Product ID #6 showed extensive deterioration. No other products showed significant additional deterioration at month nine based on visual inspection. Three products (product ID #2, #3, and #9) experienced between 0.4 and 1.87 percent loss in area covered by the material on the bus lane.

Product ID #4 and #8 showed slight deterioration, with 2.99 percent and 4.59 percent loss of coverage, respectively. One product (Product ID #7) experienced a significant decrease in coverage (91 percent) after a period of traffic wear and weathering. This result should be discounted, however, as Product ID #7 was subject to the presence of an illegally parked truck prior to the end of the recommended curing time. The presence of the truck on the setting product likely impacted its durability.

Table 4. Durability Testing Results for Red Bus Lane Treatments

Product ID / Name	October 2010 Photo	April 2011 Photo	% Coverage Oct 2010	% Coverage Apr 2011	% Reduction in Coverage*
2			100.0	98.13	1.87
3			100.0	99.16	0.84
4			100.0	95.41	4.59
5			100.0	100.0	0.00
6			100.0	100.0	0.00

Product ID / Name	October 2010 Photo	April 2011 Photo	% Coverage		% Reduction in Coverage*
			Oct 2010	Apr 2011	
7			100.0	NA	NA
8			100.0	97.01	2.99
9			100.0	99.63	0.37

* Values in brackets [ ] represent percent coverage if manhole covers and “Bus Only” symbols are excluded from analysis.

Skid Resistance

Table 5 shows the results of the friction analysis. For each product, the friction measured using the DF tester at 20 km/h (12 mph), mean profile depth (mm), the international friction index (IFI), and friction computed for vehicle traveling at 30 mph (New York City speed limit), are shown for the October 2010 and April 2011 data collection periods. The percent change in friction between the October 2010 and April 2011 periods is also shown in Table 5.

Table 5. Friction Testing Results

Product ID	DF Tester Friction at 12 mph		CT Meter Mean Profile Depth (mm)		Int'l Friction Index (IFI, F60)		Friction for Vehicles at 30 mph		% Reduction in Friction*
	Oct 2010	Apr 2011	Oct 2010	Apr 2011	Oct 2010	Apr 2011	Oct 2010	Apr 2011	
2	0.37	0.47	0.54	0.39	0.22	0.23	0.27	0.30	-11.1
3	0.81	0.59	0.88	0.62	0.47	0.32	0.53	0.38	28.3
4	0.81	0.65	2.02	1.33	0.56	0.43	0.60	0.47	21.7
5	0.41	0.47	1.51	0.99	0.31	0.31	0.34	0.35	-2.9
6	0.54	0.61	0.60	0.45	0.30	0.29	0.36	0.36	0.0
7	0.34	0.46	0.75	0.59	0.23	0.27	0.27	0.32	-18.5
8	0.41	0.50	0.77	0.58	0.27	0.28	0.31	0.34	-8.8
9	0.62	0.72	1.52	1.17	0.43	0.46	0.46	0.51	-10.9
Untreated Asphalt	0.42	--	0.62	--	0.25	--	0.30	--	--
*A negative sign indicates that friction increased between October 2010 and April 2011									

The percent reduction in friction for each red bus lane treatment was computed using the following equation:

$$\Delta Friction = \frac{Avg.\%_{October\,2010} - Avg.\%_{April\,2011}}{Avg.\%_{October\,2010}} \times 100 \qquad (2)$$

where:

- $\Delta Friction$ = percent reduction in friction for the red bus lane treatment between the period in October 2010 and April 2011.
- $Avg.\%_{October2010}$ = friction for red bus lane treatment in October 2010
- $Avg.\%_{April2011}$ = friction for red bus lane treatment in April 2011.

The results of the friction testing to date indicate that one product (ID #6) did not experience any change in friction after a period of traffic wear and weathering. Two products (ID #3 and #4) experienced a loss of friction after a period of winter wear and weathering. Five products (ID #2, #5, #7, #8 and #9) experienced friction gains after a period of traffic wear and weathering. This is most likely because these products contain some form of aggregate in the product mixture that becomes more exposed at the surface after a short period of traffic wear (tire abrasion).

The research team also recorded friction measurements on the untreated asphalt (non-bus lanes) along a travel lane adjacent to the red bus lane treatments. A friction value of 0.30 was determined for vehicle traveling at 30 mph based on the DF tester and CT meter readings. Based on the data shown in Table 4, two treatments (ID #2 and #7) had friction levels less than untreated asphalt based on the October 2010 data; however, all red bus lane treatments had friction values of at least 0.30 in April 2011.

Qualitative Observations on Surface Pre-Treatment

The field test also provided the study team with the opportunity to qualitatively evaluate the impact of various surface pre-treatment techniques on red bus lane treatment durability. Three products (ID #4, #8, #9) had minimal or no surface pre-treatment. Product ID #6 was applied with some pre-treatment, including power washing to remove surface oils and dirt and scarification of the existing markings. Of these treatments, Product ID #4 and Product ID #6 showed the highest level of coverage loss of the eight products tested (when including the visual inspection of the products after nine months), while Product ID #8 and Product ID #9 performed well. Product ID #2, Product ID #3, and Product ID #5 were applied with more intensive pre-treatment, including shot blasting to remove a thin layer of the pavement surface. All three of these products showed minimal coverage loss. These results indicate that aggressive pre-treatment, specifically shot blasting, plays a role in product adhesion for street paint products. Pre-treatment appears less important for asphalt concrete-based micro surfaces. Further field testing in this area is recommended.

LABORATORY TESTING

This section describes the laboratory testing methodology and results. Six of the seven the products evaluated in the laboratory were also tested in the field. A variety of procedures were used to assess the durability and skid resistance of each treatment. A life-cycle analysis was then performed using the physical laboratory testing results to compare the products.

Methodology

The purpose of the laboratory testing methodology was to assess the durability and skid resistance of the red bus lane treatments in a temperature-controlled, indoor testing facility that enabled direct comparisons of each product using the durability and skid resistance performance metrics.

Prior to performing the laboratory tests, asphalt test slabs were prepared by the NYCDOT using NYCDOT's standard asphalt cement mix. The slabs were approximately 28- by 28-inches in area, at a depth of approximately five inches (compacted). The test slabs were left outside for two weeks prior to the application of the red treatments to allow for the evaporation of excess surface oils. A sample of each red bus lane treatment was then applied on top of the asphalt test slab by the red bus lane product manufacturers invited to participate in the laboratory testing. An example of a red bus lane product applied on the asphalt specimen is shown in Figure 8.

All durability testing in the laboratory was performed using the Model Mobile Load Simulator, 3rd scale (MMLS3) [see Ref. 2 for more details]. The MMLS can apply up to 7,200 cycles per hour over an approximate four-foot distance. This enables two sample red bus lane treatments to be tested simultaneously. The MMLS has four pneumatic rolling rubber tires that operate on an oval-shaped, vertical rail system. In the case of two-axle vehicles, the MMLS3 can simulate 14,400 vehicle passes in one hour. For this project, the linear motion setting was used because a linear wear pattern will be more representative of an accelerated degradation process.

To determine the appropriate level of wear, the research team calculated the total number of buses that use the Madison Avenue bus lane between 42nd and 57th Streets, one of the busiest bus lanes in New York City. The Madison Avenue lane carries about 1,400 buses on a typical weekday, or the equivalent of 511,000 buses annually. If each bus contains two axles, the MMLS would be capable of producing this same level of trafficking in 255,500 cycles (4 pneumatic tires = 2-2 axle buses). NYCDOT requested that the initial round of testing be performed using pneumatic rubber tires and cover three simulated years of bus traffic (i.e., 766,500 MMLS cycles).

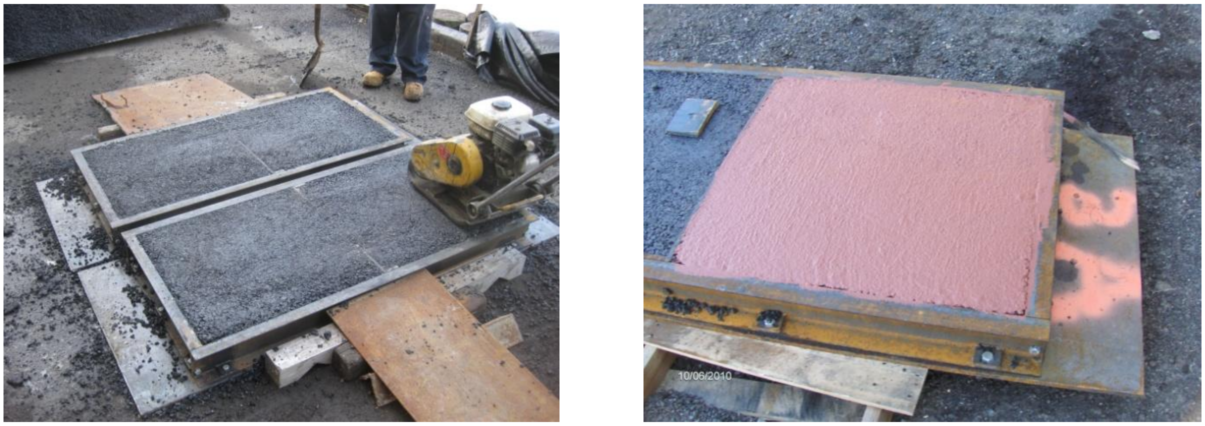


Figure 8. Forms for Red Bus Lane Specimens (left) and Red Bus Lane Product Applied to Asphalt Specimen (right)

Testing on each of the red bus lane treatments using the uncoated pneumatic rubber tires found that the products did not degrade after completing 766,500 MMLS cycles. Therefore, all subsequent MMLS testing was performed by coating two of the rubber tires with a silica-carbide material to increase the level of wear on the test slabs. Silica carbide is a powder-like substance, which is commonly used as an abrasive. Figure 9 shows the uncoated pneumatic and silica-carbide-coated tires used for the accelerated testing.

Figure 9. Uncoated Pneumatic Rubber Tire (top) and Silica-Carbide-Coated Tire (bottom)

The silica-carbide testing was performed as a means to compare the relative performance (durability) of each red bus lane product. One of the test forms (two samples) was chosen and the testing protocol was to apply 100,000 MMLS cycle increments to the products, and then take two-dimensional digital images. The digital image processing method described in chapter three was then used to assess the percent coverage of the red bus lane material in the wheel path of the MMLS. This process was repeated until the percent coverage for one of the products on the form reached a level of approximately 50 percent. The number of MMLS cycles required to reach 50 percent coverage was then applied (stopping intermittently) to each of the remaining red bus lane products.

Friction testing was performed using the circular texture meter and dynamic friction tester before and after the MMLS accelerated trafficking cycles were applied to each red bus lane product. A description of the friction testing procedure was provided in chapter three of this report.

Results

The results of the durability, friction, and thickness analyses are presented in this section.

Durability

As noted previously, accelerated testing for all products using on the pneumatic rubber tires on the MMLS resulted in no degradation to any of the products after 766,500 cycles. As such, this section shows on the results from the testing that was performed using two silica-carbide-coated tires and two uncoated tires. Table 6 shows photographs of each product before the accelerated wear process using the coated tires and after the accelerated wear process was completed. Table 6 also shows the percent of the wheel path covered by the red bus lane treatment at various wear stages (cycles).

The results of the accelerated wear analysis show that samples product ID #6 and #7 both fell below the 50 percent coverage threshold between 200,000 and 300,000 cycles, which has been defined as the point at which a red lane material will have to be re-applied. Both of these products are Portland Cement-based micro surfacing products.

Product ID #8 is the only asphalt cement-based micro surfacing product in the evaluation that did not degrade significantly after 500,000 cycles. Of the two anti-skid products tested (ID #4 and ID #5), product ID #4 did not degrade after 500,000 cycles while product ID #5 degraded to 61.7 percent coverage after 500,000 cycles. Of the two traffic paints tested (product ID #1 and #2), product ID #1 retained the higher level of surface coverage (85.2 percent) among the products, after 400,000 cycles.

To further assess the durability of the products tested in the laboratory using the MMLS, the thickness of the red bus lane products were measured before and after accelerated testing with the coated tires. This data, along with photos of the sample specimens, is shown in Table 7. Because the application or wear of the product was not always uniform over the entire surface, the thickness was measured at four locations (left, right, top, and bottom) on the sample core. An average thickness was then computed and is shown in Table 7.

The thickness analysis generally supports the digital image processing analysis. Product ID #6 and #7 have very limited product remaining on the sample core after 300,000 cycles with the coated tires. The samples that have some red product covering the asphalt surface generally had a high level of coverage after accelerated wear (i.e., product ID #1, #4, #5, and #8).

Table 6. Durability Lab Testing Results for Red Bus Treatments

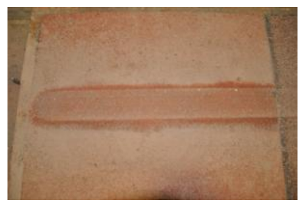
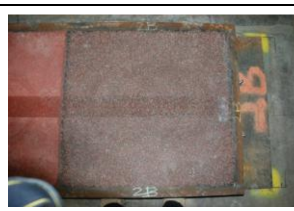
Product ID	Before Photo	After Photo	# of Cycles	% Coverage
1			begin	100
			100,000	85.2
			200,000	85.2
			300,000	85.2
			400,000	85.2
2			begin	100
			100,000	82.2
			200,000	74.9
			300,000	72.0
			400,000	61.9
4			begin	100
			100,000	100
			300,000	100
			500,000	100
5			begin	100
			100,000	86.5
			200,000	79.8
			300,000	77.9
			500,000	61.7
6			begin	100
			100,000	83.3
			200,000	78.1
			300,000	39.0
7			begin	100
			100,000	75.8
			200,000	65.7
			300,000	29.3
8			begin	100
			100,000	90.9
			300,000	90.1
			500,000	87.1

Table 7. Thickness of Red Bus Lane Products Before and After Accelerated Trafficking

Product ID	Photograph	Thickness (inches)	
		Before	After
1		Left: 0.08 Right: 0.08 Top: 0.07 Bottom: 0.07 Avg: 0.08	L: 0.04 R: 0.05 T: 0.01 B: 0.06 Avg: 0.04
2		L: 0.03 R: 0.04 T: 0.03 B: 0.04 Avg: 0.04	L: 0.02 R: 0.02 T: 0.02 B: 0.02 Avg: 0.02
4		L: 0.29 R: 0.33 T: 0.32 B: 0.32 Avg: 0.32	L: 0.15 R: 0.14 T: 0.14 B: 0.14 Avg: 0.14
5		L: 0.30 R: 0.30 T: 0.31 B: 0.32 Avg: 0.31	L: 0.30 R: 0.30 T: 0.30 B: 0.30 Avg: 0.30
6		L: 0.23 R: 0.16 T: 0.12 B: 0.18 Avg: 0.17	L: 0.00 R: 0.00 T: 0.00 B: 0.05 Avg: 0.01
7		L: 0.20 R: 0.21 T: 0.24 B: 0.18 Avg: 0.21	L: 0.00 R: 0.00 T: 0.00 B: 0.00 Avg: 0.00
8		L: 0.14 R: 0.14 T: 0.15 B: 0.16 Avg: 0.15	L: 0.07 R: 0.08 T: 0.09 B: 0.07 Avg: 0.08

Skid Resistance

Table 8 shows the results of the laboratory friction analysis. For each product, the friction measured using the DF tester at 20 km/h (12 mph), mean profile depth (mm), the international friction index (IFI), and friction computed for a vehicle traveling at 35 mph, are shown for the corresponding MMLS-3 accelerated wear cycles.

As seen in Table 8, the surfaces applied with product ID #1, #4, and #5 experience little change (or slight increases) in macro-texture throughout the accelerated wear process based on the CT Meter mean profile depth (MPD) measurements. The remaining materials all experienced a decrease in macro-texture. This is likely the result of the accelerated wear process polishing the red treatments applied to the laboratory samples.

The reduction of the 60 km/h locked wheel friction (SN60 in Table 8) of the surfaces was generally proportional to the MMLS-3 cycles, but the loss was non-linear and, in some cases, friction increased after applying MMLS-3 cycles. Product ID #5 shows a total of approximately 17 percent frictional loss, while product ID #4 and ID #8 exhibit seven- and ten-percent friction loss, respectively. Product ID #2 experienced 15 percent friction loss during the accelerated wear process, while product ID #1 experienced a three-percent increase in friction. Product ID #6 and ID #7 experienced a three- and five-percent friction loss, respectively, after the application of more than one million traffic cycles. With the exception of product ID #5, all red bus lane materials tested in the laboratory maintained a friction level above 0.30.

Table 8. Laboratory Friction Measurements

Prod. ID	Cycles (1,000s)	DF Tester (12 mph)	CT Meter Mean Profile Depth (mm)	S_p	International Friction Index, F60	SN60
1	0	0.50	0.395	49.67	0.25	0.34
	100	0.47	0.455	55.05	0.25	0.34
	255	0.46	0.432	52.92	0.24	0.33
	512	0.52	0.433	53.00	0.26	0.36
	760	0.50	0.370	47.35	0.24	0.34
	1,160	0.48	0.459	55.39	0.25	0.35
2	0	0.51	0.596	67.65	0.29	0.39
	100	0.51	0.600	67.99	0.29	0.38
	255	0.47	0.597	67.76	0.27	0.36
	512	0.48	0.565	64.85	0.27	0.36
	760	0.45	0.583	66.45	0.26	0.35
	1,160	0.42	0.570	65.33	0.25	0.32
4	0	0.58	0.358	46.34	0.26	0.37
	100	0.58	0.437	53.41	0.28	0.39
	255	0.45	0.435	53.22	0.24	0.32
	512	0.48	0.432	52.92	0.24	0.34
	760	0.53	0.401	50.15	0.26	0.36
	1,260	0.48	0.421	51.95	0.24	0.33
5	0	0.47	1.229	124.46	0.33	0.37
	100	0.43	1.144	116.79	0.31	0.34
	255	0.40	1.278	128.79	0.30	0.31
	512	0.28	1.299	130.70	0.23	0.30
	760	0.35	1.141	116.57	0.26	0.27
	1,260	0.36	1.262	127.37	0.27	0.27
5	0	0.42	1.207	122.48	0.30	0.33
	100	0.39	1.349	135.18	0.29	0.29
	255	0.34	1.277	128.75	0.26	0.25
	512	0.31	1.231	124.61	0.24	0.23
	760	0.34	1.217	123.34	0.26	0.26
	1,260	0.32	1.241	125.54	0.25	0.24
6	0	0.65	0.852	90.59	0.39	0.51
	100	0.63	0.784	84.54	0.37	0.49
	255	0.55	0.834	89.02	0.34	0.44
	512	0.77	0.737	80.32	0.43	0.58
	760	0.69	0.816	87.42	0.40	0.53
	1,060	0.65	0.795	85.51	0.38	0.50
7	0	0.61	1.091	112.05	0.39	0.49
	100	0.61	0.841	89.62	0.36	0.48
	255	0.59	0.905	95.42	0.37	0.47
	512	0.56	0.887	93.77	0.35	0.45
	760	0.52	0.942	98.7	0.34	0.42
	1,060	0.6	0.932	97.77	0.37	0.48
8	0	0.91	1.983	192.07	0.62	0.72
	100	0.85	2.044	197.52	0.59	0.67
	255	0.85	1.917	186.16	0.58	0.67
	512	0.83	1.927	187.02	0.57	0.65
	760	0.83	1.830	178.32	0.56	0.65
	1,260	0.83	1.718	168.33	0.56	0.66

LIFE CYCLE ANALYSIS

To perform a product life-cycle analysis, an estimate of the number of bus passes required for a red bus lane treatment to reach the end of its effective service life was required. The project team defined the threshold value as 50 percent coverage over the surface area of the product (bus lane or laboratory sample). This is consistent with the Federal Aviation Administration's *Development of Methods for Determining Airport Pavement Marking Effectiveness* research study (Ref. 3).

Two methods could be used to determine the number of MMLS cycles required to reach the 50 percent coverage threshold. The first is to use a statistical model to predict, based on the digital image processing data provided in Table 6, when the coverage threshold is reached. In some instances, however, a clear trend for four or five observations may be difficult to establish. Therefore, an alternative approach was used based on the materials thickness data in Table 7. The "before" and "after" period thicknesses were used to extrapolate the number of cycles (based on a linear degradation process) required until the red bus lane product would reach an average thickness of 0.01 inches. This thickness was chosen because, based on the data in Table 7 product ID #6 had very limited coverage when the average thickness was 0.01 inches. Product ID #2 had 61.7 percent coverage (see Table 7) when the "after" period thickness of the sample was an average of 0.02 inches.

Table 9 shows the degradation equation or extrapolation method for each of the seven samples, as well as the number of MMLS cycles necessary to reach the 50 percent coverage threshold. A regression equation and the extrapolation method were both used to evaluate product ID #4 because the variability explained by including MMLS cycles in the model was 58.9 percent, and because the "Cycles" independent variable was not statistically significant in the regression model. Product ID 4 and ID #8 have the greatest expected service life based on the laboratory durability analysis. Product ID #6 and #7 both fell below the coverage threshold during testing and thus have the shortest expected service life.

Table 9. Number of MMLS Cycles Required to Reach Product Coverage Threshold

Product ID	Method to Compute Coverage Threshold	Degradation or Extrapolation Equation	Model Descriptors	MMLS Cycles to Reach 50% Coverage Threshold
1	Extrapolation	$\frac{0.08-0.04}{0-400{,}000}=\frac{0.04-0.01}{400{,}000-x}$	N/A	700,000
2	Linear Regression	$Coverage = 95.48 - 0.000086 \times Cycles$	R^2 = 90.1% t-stat: -6.12*	526,000
4	Linear Regression	$Coverage = 96.83 - 0.000021 \times Cycles$	R^2 = 58.6% t-stat: -2.30	2,230,000
	Extrapolation	$\frac{0.32-0.14}{0-500{,}000}=\frac{0.14-0.01}{500{,}000-x}$	N/A	861,100
5	Linear Regression	$Coverage = 96.7 - 0.000071 \times Cycles$	R^2 = 94.1% t-stat: -8.04*	657,750
6	Linear Regression	$Coverage = 103.33 - 0.00019 \times Cycles$	R^2 = 82.9% t-stat: -3.94*	281,000
7	Linear Regression	$Coverage = 101.03 - 0.00022 \times Cycles$	R^2 = 93.1% t-stat: -6.45*	230,000
8	Extrapolation	$\frac{0.15-0.08}{0-500{,}000}=\frac{0.08-0.01}{500{,}000-x}$	NA	1,000,000

*The t-statistic for the "Cycles" independent variable is statistically significant at 95-percent confidence level.

CONCLUSIONS

The three top performing products from strictly durability perspective, which all maintained at least 80 percent coverage in the field or lab testing, were product ID #1, #4, and #8. Product #1 was an epoxy-based street paint, product #4 was an epoxy and aggregate anti-skid treatment, and product #8 was an asphalt concrete-based micro surfacing product. These products were as follows:

- Product ID #1: StreetBond CL, a Quest Construction product
- Product ID #4: Mark 177 System, a Dow POLY-CARB product
- Product ID #8: Cape Seal, a New York Bituminous Products Corporation product

The Portland Cement-based micro surfaces (product ID #6 and #7) demonstrated inferior durability relative to the other products tested.

Combining the quantitative durability results with qualitative observation and agency experience, NYCDOT made the following conclusions regarding the installation of red lanes in New York City:

- Portland cement-based micro surface products are not an effective red lane treatment on asphalt concrete and Portland cement surfaces.
- Although very durable, products designed primarily as anti-skid surface treatments tend to attract more dirt and debris than other products due to their rough surface texture.
- Epoxy street paint products provide a relatively durable red bus lane solution for new asphalt concrete surfaces.
- Asphalt concrete-based micro surfaces are a promising red bus lane treatment for new and existing asphalt concrete surfaces and should be evaluated further.
- Aggressive pre-treatment, including shot blasting and power washing, appears to improve the performance of epoxy street paints on existing asphalt roadways and should be evaluated further.

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