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EVALUATION OF URBAN ASPHALT CONCRETE RUTTING

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ABSTRACT

Inspection of thirty-six Toronto Transportation pavement locations with asphalt concrete rutting, and detailed field and laboratory evaluation of eight curb lane/bus bay locations with severe rutting, indicated the areas of concern are associated with commercial vehicle usage, particularly buses, in curb lanes, bus bays and turn lanes. Buses make up 60 to 95 percent of the total static and dynamic equivalent loadings for the curb lanes considered. There is growing interest (Transport Canada for instance) in such bus influences on pavement performance. Use of high stability, rut resistant asphalt concrete has been successful in terms of overall pavement performance. There is no rutting problem for resurfaced composite pavements, particularly if the old asphalt concrete is removed down to the concrete base. There appears to be a rutting problem with the resurfacing of some deep strength asphalt pavements, most probably related to not milling deep enough before resurfacing (minimum of 125 mm recommended). Some rutting has rapidly developed in isolated instances where the new asphalt concrete did not meet specification requirements (low in-place voids or aggregate 'bulking' for instance). New rut resistant asphalt mixes, such as large stone binder course (LSBC), high stability surface course HL 1 (with PG 64-28) and stone mastic asphalt (SMA), show enhanced performance and favourable life-cycle costing.

INTRODUCTION

In 1987/88, a Toronto Transportation study quantified the impact of heavy commercial vehicles, particularly bus operations, on Toronto Transportation's pavement system in terms of severe rutting and accelerated pavement damage (Emery and Johnston, 1990). Such asphalt concrete rutting is a high cost maintenance and rehabilitation problem, particularly for bus bays and curb lanes (Sweet, 1990). Improved asphalt technology rutting mitigation procedures were promptly implemented through the Toronto Transportation specifications (Toronto Transportation, 1997). Essentially, high stability levelling, binder and surface course asphalt concrete mixes with enhanced rutting resistance properties were adopted (Emery and Johnston, 1990; Toronto Transportation, 1997). Toronto Transportation continues to focus on applied urban asphalt technology and the implementation of cost effective, technically advanced pavement materials such as large stone binder course (LSBC), stone mastic asphalt (SMA) and performance graded (PG) asphalt binders (Burlie, D'Ippolito, Woodman, MacKay, Hein and Emery, 1992; Woodman, Burlie, Dhillon and Emery, 1995; Woodman, Burlie and Emery, 1996).

The Toronto Transportation rutting experience is not unique, as many agencies continue to address asphalt concrete rutting problems (Emery, 1990; Sontowski, 1995). What was unique, until recently, was Toronto Transportation's focus on bus-pavement interaction issues and the need for enhanced bus routes' construction and maintenance funding. The influence of bus operations on pavement systems has recently become of interest to Transport Canada's Transportation Development Centre through cost/benefit studies of lighter urban transit buses, including pavement structural design and deterioration impacts and costs [Beauchemin-Beaton-Lapointe Inc., 1994]. It is now widely recognized that bus operations have a significant impact on pavements and bus design research should also consider potential reduction of damage to urban pavements [Transportation Research Board, 1995].

There is still some localized asphalt concrete rutting, even in new asphalt pavements, being observed by Toronto Transportation, mainly in curb lanes and bus bays, that could be due to several interacting factors such as:

1. hot-mix asphalt materials, mix design and/or production not meeting specified requirements;
2. compaction of hot-mix asphalt not meeting specified requirements;
3. early heavy vehicle traffic on asphalt concrete mat before it has adequately cooled;
4. old asphalt concrete binder course(s) susceptible to rutting not removed (milled) to an adequate depth; and/or
5. rutting resistance of the current high stability mixes is not adequate in some heavy traffic situations.

It was considered important to update the 1987/88 study to determine if the observed rutting is a function of specification compliance (factors 1, 2 and/or 3), resurfacing/ reconstruction design (factor 4) and/or the new asphalt concrete not being adequately rut resistant (factor 5). Any asphalt concrete rutting concerns must be effectively dealt with as the impact on pavement construction, rehabilitation and maintenance operations is both costly and causes user delays.

EVALUATION PLAN FOR ASPHALT CONCRETE RUTTING

An evaluation plan for asphalt concrete rutting was developed:

1 Selection of six test cut locations on pavements reconstructed or overlaid before 1990, with observable severe curb lane/bus bay rutting, from some thirty potential locations based on: the Toronto Transportation Pavement Management System; interaction with Toronto Transportation staff; and inspection of potential locations. Additionally, cores were taken from a recent, localized, rutting problem area of Markham Road. The inspection of potential locations also provided an excellent overview of the asphalt concrete rutting situation and extent.

2. Coring and/or inspection of bus bay locations of pavements reconstructed or overlaid recently (1995 to 1997) where slight to severe rutting has already appeared. Additionally, cores were taken from an area on The Queensway exhibiting severe ripples and rutting.

3. Completion of a detailed technical evaluation for each of the selected six test cut locations:
   a. Measuring transverse profiles in rutted areas with a digital incremental profiler (DipstickR);
   b. Measuring transverse profiles in adjacent areas not exhibiting rutting;
   c. Coring and cutting to remove a 'continuous' transverse section of asphalt concrete pavement of the worst rutted profile, including measurements to determine the zone of rutting within the section as well as the condition of concrete base or granular substrate;
   d. Coring an adjacent area not exhibiting rutting, including visual observations; and
   e. Density (bulk relative density (BRD) and maximum relative density (MRD), percent compaction, air voids, stability, flow, asphalt cement content, aggregate gradation, aggregate crushed content and petrography, and Abson recovery asphalt cement penetration/viscosity of each binder and surface course lift of interest.

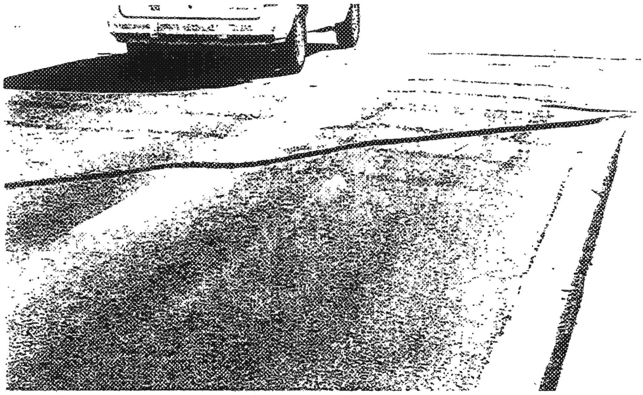
4. Documentation of field and laboratory observations with distress data and photographs, including pavement history, traffic information and current pavement condition.

EVALUATION OF ASPHALT CONCRETE RUTTING

The six locations (sections) mentioned are described in Table 1 in terms of roadway, nearest intersection, location selection criteria and specific lane/location. Severe rutting of curb lane/bus bay areas was generally involved for each location, as shown by the typical Photograph 1 for Finch Avenue East at Victoria Park Avenue (Location 2). It is clear that one cause of rutting for some resurfacing projects is related to not milling out an adequate depth of the existing (old) rutted section. Typically, the rutting of curb lanes/bus bays occurs in 'pairs' for each direction on bus routes with a curb lane/bus bay performance problem.

TABLE 1
EVALUATION OF ASPHALT CONCRETE RUTTING, KEY LOCATIONS

NO.	ROADWAY	NEAREST INTERSECTION	LOCATION SELECTION CRITERIA	SPECIFIC LANE/LOCATION
1	Steeles Avenue East	West of Highway 404	High Occupancy. Vehicle (HOV) Lane. High passenger vehicle and bus volumes. Considerable rutting following rehabilitation.	Westbound curb/HOV lane just east of the main entrance to the 'Shoppes at 404 and Steeles'
2	Finch Avenue East	Victoria Park Avenue	High severity rutting (45 mm).	Eastbound curb lane/bus bay just west of the intersection.
3	Lawrence Avenue West	Keele Street	All traffic impacts pavement, major right turn lane with traffic proceeding north to Highway 401.	Westbound curb lane/bus bay just east of the intersection.
4	Lawrence Avenue West	Keele Street	Compare with No. 3. This section is a bus bay with the majority of traffic being bus traffic.	Eastbound curb lane/bus bay just east of the intersection.
5	Leslie Street	York Mills Road	Composite pavement (only section). Mostly bus traffic (bus bay).	Southbound curb lane/bus bay just south of the intersection.
6	York Mills Road	Leslie Street	Recent widening of intersection. Many patch sections.	Eastbound curb lane/bus bay just west of the intersection.



PHOTOGRAPH 1 Severe rutting in Finch Avenue East eastbound curb lane/bus bay just west of Victoria Park Avenue intersection (Location 2 test cut section).

Five of the six locations (sections) involved deep strength (asphalt concrete) pavement sections. The Leslie Street section (Location 5) involved a composite pavement (asphalt concrete surface with concrete base), which is the predominant pavement type for Toronto Transportation's pavement system. It appears that ongoing rutting of old deep strength asphalt pavement sections is the most common rutting problem involved. This type of rutting is shown schematically for the York Mills Road Location 6 (Section 6) in Figure 1. The original rutting susceptible binder course is still subjected to enough tire loading shear stress to continue rutting. It would appear that a minimum thickness of 125 mm, and preferably 150 mm, of high stability mix (typically HL 1 surface course and HL 8 (HS) binder course) is required for the resurfacing of such old deep strength asphalt pavements. Similarly, all of the old asphalt concrete should be removed down to the concrete base for the resurfacing of old composite pavements.

The recently overlaid (1995-1997) locations are summarized in Table 2. Slight to severe rutting of new pavements is related to mainly hot-mix asphalt materials, mix design an/or production not meeting specified requirements, and the mix used on the project not having adequate rutting resistance. Severe ripples of The Queensway were mainly due to poor quality surface and binder course asphalt mixes.

The roadway, field and laboratory data for the six locations (paved before 1995) is summarized in Tables 3 and 4. From the specific information for the six locations selected for detailed evaluation, and particularly the inspection of some thirty sections with rutting of interest to Metro Transportation staff, the following comments can be made on this localized rutting:

vehicles, particularly buses, in curb lanes near stop bars, bus bays, and left turn and right turn lanes with heavy vehicles;

2. There does not generally appear to be a rutting problem for composite pavements resurfaced (only a few constructed/reconstructed) after 1988 when high stability mixes were adopted;
3. There does seem to be a rutting problem with the resurfacing of some deep strength asphalt pavements (1. locations typically), most probably related to not milling the old asphalt binder course out deep enough before resurfacing (quite often these have localized patches or bus bay rutting repairs); and
4. Where the hot-mix asphalt in isolated instances has not met current specification requirements, for instance, some rutting has rapidly developed.

Regardless, the 1996/98 site inspections, as during the 1987/88 Metro Transportation rutting study, have clearly indicated the significant impact of buses on Toronto Transportation's pavement system performance (deterioration) and the maintenance activities costs of Toronto Transportation.

TABLE 2
EVALUATION OF NEW ASPHALT CONCRETE RUTTING, KEY LOCATIONS

NO.	ROADWAY	NEAREST INTERSECTION	LOCATION SELECTION CRITERIA	SPECIFIC LANE/LOCATION
1	Brown's Line	From Coules Ct. to Burlingame Rd.	Heavy (bus and truck) traffic curb northbound lane and areas (stop bar) near intersections Slight to moderate rutting (18 mm) of DFC surface course paved in 1996.	Intersection with Valermo Drive and Horner Avenue.
2	Finch Avenue	Warden Avenue	Localized rutting (up to 26 mm) in bus bays repaired in 1997 in areas where bus wheels stop.	Finch Avenue bus bays.
3	Jane Street	Weston Road	Up to 37 mm deep rutting in bus bay paved in 1997. Asphalt concrete mix in the bay badly segregated (very fine mix).	Northbound bus bay on Jane Street.
4	Banting Avenue	Sheppard Avenue	Bus traffic to-and-from the TTC bus station. Up to 22 mm deep rutting in left turn lane paved in 1996.	Left turn lane at the intersection with Sheppard Avenue.
5	Warden Avenue	Lawrence Avenue	Very slight rutting (up to 8 mm) in curb lanes/bus lanes.	Only curb lanes/bus lanes on Warden Avenue.
6	The Queensway	Colborne Lodge Drive	Severe ripples in all three westbound lanes before the intersection with Colborne Lodge Drive (the most severe in the middle lane). Severe rutting in curb lane.	All three lanes.

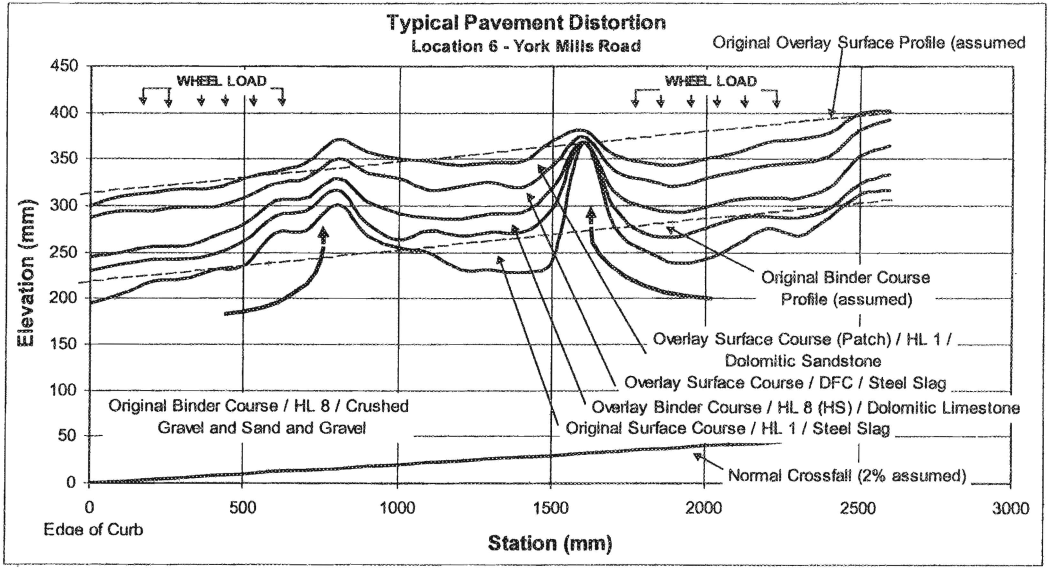


FIGURE 1 Typical Distortion of Pavement Under Repeated Overloads (Location 6 – York Mills Road)

TABLE 3
SUMMARY OF ROADWAY DATA

DESCRIPTION	SECTION (as in Table 1)					
	1	2	3	4	5	6
AADT 24 Hour	21995	19532	13411	20410	22358	NA
AADT 8 Hour	9752	8216	7910	8475	10713	5404
No. of Lanes	3	4	3	3	3	5
Compounded 18 year Growth Rate	3.3%	2.6%	1.5%	1.5%	1.3%	0.6%
Percent Trucks	1.9	1.2	5.9	7.0	1.1	5.4
No. of Buses/day	189	324	310	300*	63	200*
Construction History/Pavement Type	RC 1980/ Deep Strength	RC 1973/ Deep Strength	OL 1984/ Deep Strength	OL 1984/ Deep Strength	OL 1987/ Composite	OL 1972/ Deep Strength
Visual Condition Rating Ride Comfort Rating	7.4 Good to Excellent	6.5 Good	6.8 Good	6.8 Good	8.0 Good to Excellent	6.6 Fair to Good

TABLE 4
SUMMARY FIELD AND LABORATORY DATA

Description	Section					
	1	2	3	4	5	6
Rut Depth of Cut Section, mm	38	45	45	45	Nil	43
Pavement Type	Deep Strength	Deep Strength	Deep Strength	Deep Strength	Composite	Deep Strength
Average Thickness, mm	300	240	310	250	120 + 225(PCC)	335
Description of Mixes Overlay Surface Course Overlay Binder Course Original Surface Course Original Binder Course	 DFC HL 8 (HS) - HL 8	 DFC HL 8 - HL 8	 HL 1 - - HL 8	 HL 1 - - HL 8	 DFC HL 8 - HL 8 over PCC	 HL 1/DFC HL 8 (HS) HL 1 HL 8

IMPACT OF VEHICLES ON PAVEMENTS

In order to quantify the impact of various vehicle types (cars, trucks and buses) on Metro's pavement system, the 1987/88 rutting study approach was updated to reflect current traffic data and the use of the 1993 AASHTO "Guide for Design of Pavement Structures" to determine equivalent single axle loadings (ESALs) [AASHTO, 1993] essentially a fourth power relationship [1]. In order to determine ESALs, it is important to adopt a realistic 'allowable' front single tire steerable single axle loading. Based on the technical literature [Clayton and Plett, 1990; Hutchinson and Mallett, 1990; Hutchinson, 1989; Sebaaly and Tabatabaee, 1992; Croney and Watkins, 1974], studies [RTAC, 1986; Hajek, Kennepohl and Billing, 1992] and codes [AASHTO, 1992; MTO, 1991; MTO, 1987], it appears that the Ontario legal ('MTO') 49.0 kN front axle loading for an axle equivalency factor of 1.00, is appropriate. As it is known that there is a dynamic shift forward during braking of vehicles (from rear axle(s) to front axle), the dynamic shift values developed by Hutchinson et al for general braking operations were adopted [Hutchinson, Rillet, Green, Haas, 1989].

The historical vehicle volumes (total vehicles and TTC buses) for the six locations indicate a general trend of increasing volumes. The vehicle impacts in terms of load equivalency (Table 5) and estimated weekday vehicle volumes and equivalent single axle loadings (Table 6) were used to determine the impact of each vehicle type by volume and ESALs for each curb lane/bus bay location, both static and dynamic. Buses make up about 60 to 95 percent of both the total daily static and dynamic ESALs for the curb lanes considered.

This updating of the 1987/88 rutting study consideration of the impact of various vehicle types again indicates the significant contribution of bus operations to the deterioration of Toronto's curb lanes and bus bays. Such bus impacts clearly warrant consideration in terms of equitable curb lane/bus bay usage costing.

TABLE 5
VEHICLE LOAD IN TERMS OF LOAD EQUIVALENCY

AXLE LOAD IN KN AND AXLE EQUIVALENCY FACTORS														
Vehicle Description	Front Axle (Single Tire Single Axle)			Rear Axle (Dual Tire Single Axle)			Rear Axle (Dual Tire Tandem Axle)			Equivalent Axle Loads (LEF)		AASHTO Weighted LEF		
	Axle Load	FA	FM	Axle Load	FA	FM	Axle Load	FA	FM	Total FA	Total FM	% of Time	Contribution	Total
Standard AASHTO Truck	49.0	1.00	1.0	80.0	1.00	0.44	129	1.00	0.23	-	-	-	-	-
Standard MTO Truck	49.0	1.00	1.0	98.0	2.25	1.00	187	4.43	1.00	-	-	-	-	-
TTC Bus (General Motors, Model TC 40102A)														
Static Load (31% Front/69% Rear)														3.47
Light Load Capacity	37.3	0.34	0.34	82.9	1.15	0.51	-	-	-	1.49	0.85	10%	0.15	
Medium Load Capacity	43.5	0.62	0.62	96.7	2.14	0.95	-	-	-	2.76	1.57	60%	1.66	
Manufacturer Crush Capacity	47.4	0.88	0.88	105.5	3.02	1.34	-	-	-	3.90	2.22	Na	Na	
Metro's Observed Crush Capacity	51.8	1.25	1.25	115.1	4.29	1.91	-	-	-	5.54	3.15	30%	1.66	
Dynamic Load (43% Front/57% Rear)														4.14
Light Load Capacity	51.7	1.24	1.24	68.5	0.54	0.24	-	-	-	1.78	1.48	10%	0.18	
Medium Load Capacity	60.3	2.30	2.30	79.9	1.00	0.44	-	-	-	3.29	2.74	60%	1.98	
Manufacturer Crush Capacity	65.8	3.25	3.25	87.2	1.41	0.63	-	-	-	4.65	3.87	Na	Na	
Metro's Observed Crush Capacity	71.8	4.61	4.61	95.1	2.00	0.89	-	-	-	6.61	5.50	30%	1.98	
Standard MTO Truck in Toronto Transportation														
Unloaded	49.0	1.00	1.00	-	-	-	79.4	0.14	0.03	1.14	1.03	50%	0.57	3.29
Loaded	49.0	1.00	1.00	-	-	-	187	4.43	1.00	5.43	2.00	50%	2.72	

TABLE 6
ESTIMATED WEEKLY VEHICLE VOLUME AND EQUIVALENT SINGLE AXLE LOADS (ESAL)

LOCATION			VEHICLE VOLUME				EQUIVALENT SINGLE AXLE LOAD					
No.	Street Name	Lane	Type of Vehicle	AADT	Percent of AADT	Total No. of Vehicles	Static Loading Condition			Dynamic Loading Condition		
							LEF	Subtotal	Total	LEF	Subtotal	Total
1	Steeles Avenue East	Westbound Curb Lane	Buses	189	100%	189	3.47	656		4.14	782	
			Trucks	470	25%	118	3.29	387		3.29	387	
			Cars	22000	25%	5500	0.0004	2	1045	0.0004	2	1171
2	Finch Avenue East	Eastbound Right Turn Lane	Buses	324	100%	324	3.47	1124		4.14	1341	
			Trucks	40	100%	40	3.29	132		3.29	132	
			Cars	2630	100%	2630	0.0004	1	1257	0.0004	1	1474
3	Lawrence Avenue West	Westbound Right Turn Lane	Buses	310	100%	310	3.47	1076		4.14	1283	
			Trucks	240	100%	240	3.29	790		3.29	790	
			Cars	4250	100%	4250	0.0004	2	1867	0.0004	2	2075
4	Lawrence Avenue West	Eastbound Merge Lane	Buses	300	100%	300	3.47	1041		4.14	1242	
			Trucks	150	25%	38	3.29	123		3.29	123	
			Cars	2030	25%	508	0.0004	0	1165	0.0004	0	1366
5	Leslie Street	Southbound Merge Lane	Buses	63	100%	63	3.47	219		4.14	261	
			Trucks	15	25%	4	3.29	12		3.29	12	
			Cars	1280	25%	320	0.0004	0	231	0.0004	0	273
6	York Mills Road	Eastbound Right Turn Lane	Buses	200	100%	200	3.47	694		4.14	828	
			Trucks	15	100%	15	3.29	49		3.29	49	
			Cars	1280	100%	1280	0.0004	1	744	0.0004	1	878

RUTTING OF NEW PAVEMENTS

Rutting, often with associated flushing and bleeding, of newly laid asphalt surface course lifts was limited to heavy (bus and truck) traffic curb lanes/bus lanes. The DFC surface course placed on Brown's Line in 1996 exhibited progressive medium severity rutting and flushing/bleeding (Photograph 2) due to the high percentage of flat or elongated particles in the trap rock coarse and fine aggregate. Following placement, the flat or elongated particles realigned themselves, along with some aggregate fracturing, from kneading action of heavy traffic wheel loading, thereby causing the 'bulked' mix to 'collapse' (densify) from the surface downwards. Heavy traffic was probably also allowed back on newly placed DFC surface course before it had cooled adequately, thus increasing this early densification, flushing and rutting.

PHOTOGRAPH 2 Rutting and flushing of newly placed DFC (1996) near the intersection with Valermo Drive (looking north).

The HL 1 surface course placed on the Jane Street/Weston Road intersection in 1997 exhibited severe rutting in curb lane/bus lane areas by August 1998 due to severe variability during production of the asphalt mix. Loads of very coarse mix were followed by loads of very fine mix. The fine surface course mix has severely rutted.

The rutted bus bay pavement at the intersection of Finch Avenue and Warden Avenue was repaired in 1997. A 1998 inspection identified that the repaired areas have already developed localized rutting up to 26 mm deep in the areas where bus wheels stop. A coring investigation indicated that only about 70 to 80 mm of the existing pavement was milled out and replaced with the new HL 1 mix, instead of the recommended 150 mm. The new HL 1 surface course was placed in a single lift up to 82 mm thick.

Moderate to severe rutting (up to 22 mm deep) was observed in the 1996 pavement placed in the left turn lane on Banting Avenue at the intersection with Sheppard Avenue, with only very slight rutting (3 mm deep) observed in the right turn lane. The pavement in this area is subjected to high static loads that cause permanent deformation of asphalt concrete. It is considered most likely that the asphalt concrete mixes used at the approach to the intersection did not have sufficient resistance to permanent deformation to withstand the very localized bus wheel loadings of a static mode.

The key recommendations to avoid early rutting are:

1. use 'cubical' aggregates and avoid the use of aggregate with a high or variable flat or elongated particles content;
2. place consistent hot-mix asphalt mixes meeting specification requirements;
3. do not allow heavy vehicles on newly laid asphalt layer until the mat cools below 60°C;
4. if a repair of a severely rutted curb lane/bus lane area is required, mill out 150 mm of the existing asphalt pavement and replace it with two lifts of binder course and one lift (40 mm) of surface course; and
5. select Superpave performance graded asphalt cement (PGAC) two grades stiffer than that recommended based solely on the design high temperature for the project location (for instance PG 70-28 for a PG 58-28 location).

NEW ASPHALT MIXES

An important aspect of the study that surfaced was the detailed laboratory consideration of new mix types that should have enhanced performance, including resistance to rutting. After all of the previous discussion of asphalt concrete rutting, it is very important to note that most of Toronto Transportation's pavement system does not exhibit any significant rutting. The introduction of high stability mixes after the 1987/88 study appears to have been quite successful.

Asphalt technology has evolved to meet the demands of increasing traffic and heavier loadings for a wide range of environmental conditions. There is also a concern with the durability of rather harsh, low asphalt cement content, higher stability surface course mixes, particularly Dense Friction Course (DFC). For these reasons, Toronto Transportation has adopted several new asphalt mixes following project trials and laboratory evaluations: large stone binder course (LSBC); stone mastic asphalt (SMA); SHRP performance graded asphalt binders (PG); and High Stability binder course incorporating 10 percent recycled asphalt pavement (HL 8 (HS, 10% RAP)) [Woodman, Burlie, Dhillon, and Emery, 1995].

The observation and testing of new asphalt mix types such as HL 8 (HS, 10% RAP), LSBC, SMA and HL 1 (PG 64-28) during placement, and subsequent monitoring, are very important to assessing the technical advantages involved. However, in order to gain information on potential behaviour over the pavement service life, it is necessary to adopt some form of asphalt concrete characterization that enables prediction of long-term performance. The most important characteristics to Toronto Transportation are resistance to permanent deformation (rutting), durability and resistance to cracking (fatigue).
The overall durability behaviour of the asphalt mixes is being monitored with the Toronto Transportation Pavement Management System that considers distresses (ravelling for instance) in terms of type, severity and extent. The basic mechanistic properties of resilient modulus, resistance to fatigue and resistance to permanent deformation are being used for comparative characterization of the fatigue endurance and rutting potential of new asphalt mixes [Woodman et al, 1995]. This testing has been completed in the Nottingham Asphalt Tester (NAT).

For surface course, it would appear that SMA (0.3 percent cellulosic fibre, 5.3 percent polymer modified asphalt cement) has exhibited the best overall potential performance. While SMA has a higher initial cost, it appears that it could be effective on a life-cycle cost basis for major routes with high performance, durability and frictional requirements. On balance, it would appear for surface course that the LSBC, HL 8 (HS) and HL 8 (HS, 10% RAP) mixes all meet the performance objectives, with the LSBC probably having some structural and cost advantages.

COST CONSIDERATIONS

There are two pavement cost considerations to be dealt with in assessing asphalt concrete rutting and the impact of heavy commercial vehicles, particularly buses - initial cost and life-cycle cost. While most pavement investment decisions are still based on initial cost consideration, the life-cycle costs should be used for the economic assessment of competing technically appropriate alternatives [Provincial Auditor, 1995; MTO, 1990]. Life-cycle costing takes into account factors such as initial cost (capital cost), maintenance cost, rehabilitation cost, residual value, user costs (often not considered by agency), inflation and interest (discount rate - typically use present worth analysis). Life-cycle costing becomes particularly important when improved asphalt technology (SMA and PG for instance), with higher initial costs, but better performance with decreased maintenance and rehabilitation costs, is involved. Use of high stability mixes increases the pavement section initial construction or reconstruction cost by only about 5 to 10 percent. However, the resurfacing costs do increase much more significantly if the minimum of 125 mm of high stability mix is incorporated for deep strength asphalt pavements or down to the concrete base for composite pavements. These increased costs are estimated at \$ 6.37/m^2 (21 percent) and \$ 12.33/m^2 (47 percent) for the composite and deep strength asphalt pavements, respectively (cost of new high stability mixes and \$ 2.00/m^2 for additional milling). These are significant increments in resurfacing costs to achieve rutting resistant pavements with anticipated satisfactory performance.

For illustrative purposes, and to show that life-cycle costing is important, a life-cycle cost comparison of conventional high stability surface course (HL 1), SHRP performance graded asphalt binder (PG) surface course (HL 1 (PG 64-28)) and stone mastic asphalt surface course (SMA) deep strength pavements is summarized in Table 7. While experience data are limited, recent field performance studies have shown that SHRP performance graded asphalt binder (PG) use in surface course hot-mix asphalt is cost effective [Carrick, Fraser, Hein, Emery, 1996]. With more SMA experience and volume of usage, the life-cycle cost of SMA should become even more favourable. The recent Metro Transportation field experience with SMA (Don Mills Road, Lake Shore Boulevard and Don Valley Parkway) has been excellent [Woodman et al, 1996].

TABLE 7
LIFE-CYCLE COST COMPARISON ($/Lane-km)
30 YEAR ANALYSIS PERIOD

	CONVENTIONAL DEEP STRENGTH [b]	PERFORMANCE GRADED SURFACE COURSE	STONE MASTIC SURFACE COURSE
Initial Cost[c]	84,600	88,050	93,225
Present Worth of Maintenance Costs	8,511	3,495	2,615
Present Worth of Rehabilitation Costs	21,389	12,443	14,875
Present Worth of Residual Value	5,560	2,842	3,397
Total Present Worth of Costs	108,940	101,146	107,318
Rank	3	1	2

CONCLUSIONS

The inspection of some thirty six Toronto Transportation pavement system locations with asphalt concrete rutting, and detailed field and laboratory evaluation of eight curb lane/bus bay locations (sections) with severe rutting, indicates:

1. The rutting areas of concern for older pavements, that have not been resurfaced/ reconstructed since 1988, are associated with heavy commercial vehicle usage, particularly buses, in curb lanes near stop bars, bus bays, and left turn and right turn lanes (curb lane/bus bay severe rutting typically in 'pairs' in opposite bus route directions);
2. Some rutting has rapidly developed in isolated instances in relatively new asphalt pavements where the hot-mix asphalt has not met current specification requirements (low in-place air voids or high flat/elongated aggregate content 'bulking' for instance);
3. There is curb lane fatigue/base failure distress for some older deep strength asphalt pavement sections that probably lack adequate structural capacity for current heavy commercial vehicle usage;
4. The localized repair, often repeated, of bus bay severe rutting has often not been
5. Successful due to factors such as not milling out enough of the old asphalt concrete, not using appropriate high stability mixes and/or not achieving adequate compaction;
5. The use of high stability, rut resistant asphalt mixes (HL 8 (HS), HL 3 (HS), HL 1 and DFC) has been largely successful in terms of overall pavement performance for new, resurfaced and reconstructed composite and deep strength asphalt pavements;
6. At areas near intersections where heavy static loadings are expected (stopped bus wheel for instance) it should be considered to select Superpave performance graded asphalt cement (PGAC) two grades stiffer than that based on the design high temperature for the project location;
7. There does not appear to be a rutting problem for composite pavements resurfaced after 1988 (only a few constructed or reconstructed) when high stability mixes were regularly adopted, particularly if the old binder course asphalt was removed completely down to the concrete base;
8. There does appear to be a rutting problem with the resurfacing of some deep strength asphalt pavements (curb lanes/bus bays typically), most probably related to not milling the old asphalt binder course out deep enough before resurfacing (minimum of 125 mm high stability mixes recommended, preferably 150 mm); and
9. The significant impact of buses on pavement system performance (deterioration) and maintenance requirements was clearly apparent, as during the 1987/88 study.

There was considerable sharing of technical information during the evaluation with the recently completed Transport Canada study of lighter urban transit buses that included pavement thickness design and damage considerations. Interest in the impact of bus operations on the pavement infrastructure and its mitigation is clearly growing, along with recognition of the extra pavement construction and, particularly, maintenance, resurfacing and reconstruction costs involved with buses. For Toronto Transportation, buses make up about 60 to 95 percent of both the total daily static and dynamic ESALs, a measure of traffic impact on the pavement structure, for the curb lanes considered. The available Toronto Transportation and Transport Canada information warrants consideration of equitable curb lane/bus bay usage costing.

REFERENCES

1. Emery JJ, Johnston TH. "Rutting in the Urban Context and its Mitigation" Proceedings Canadian Technical Asphalt Association 32 340-351 (1987).
2. Sweet L. "TTC Buses Hurt Roads, Metro Says" The Toronto Star May 27 B4 (1990).
3. Toronto Transportation "Specification for Hot Mix, Hot Laid Asphaltic Concrete" Specification MT 701. New. Metric, Municipality of Metropolitan Toronto Transportation Department (1997).
4. Burlie R, D'Ippolito R, Woodman C, MacKay M, Hein D, Emery J. "Asphalt Technology for Urban Pavement Construction and Maintenance" Proceedings Canadian Technical Asphalt Association 37 184-199 (1992).
5. Woodman C, Burlie R, Dhillon P and Emery J. "Applied Urban Asphalt Technology", Proceedings Canadian Technical Asphalt Association 40 18-37 (1995).
6. Woodman C, Burlie R, Emery J. "Stone Mastic Asphalt Technology for Urban Pavements" CTAA Proceedings 41 464-483 (1996).
7. Emery JJ. "Asphalt Pavement Rutting Experience in Canada" Proceedings Canadian Technical Asphalt Association 35 80-91 (1990).
8. Sontowski P. "How to Halt Asphalt Rutting" Better Roads December 35 (1995).
9. BBL. "Cost/Benefit Analysis of Lighter Urban Transit Buses" CDT-9034, Preliminary Findings and Detailed Work Program for the Transportation Development Centre Transport Canada Beauchemin-Beaton-Lapointe Inc. Montreal (1994).
10. BBL. "Cost/Benefit Analysis of Lighter Urban Transit Buses" CDT-9034, Final Report for the Transportation Development Centre Policy and Coordination Transport Canada Beauchemin-Beaton-Lapointe Inc. Montreal (1995).
11. TRB. "Forum on Future Directions in Transportation R & D" Conference Proceedings 9 Transportation Research Board, Washington (1995).
12. AASHTO. "AASHTO Guide for Design of Pavement Structures 1993" American Association of State Highway and Transportation Officials, Washington (1993).
13. Clayton A and Plett R. "Truck Weights as a Function of Regulatory Limits" Canadian Journal of Civil Engineering 17 45-54 (1990).
14. Hutchinson BG and Mallett JJL. "Line Haul Transport Cost and Pavement Damage, Characteristics of Some Ontario Trucks" Canadian Journal of Civil Engineering 17 28-35 (1990).
15. Hutchinson BG. "Pavement Damage Implications of Ontario Bridge Formula Axle Group Weight Limits" Canadian Journal of Civil Engineering 16 693-697 (1989).

16. Sebaaly PE and Tabatabaee N. "Effect of Tire Parameters on Pavement Damage and Load-Equivalency Factors" Journal of Transportation Engineering 118, 805-819 (1992).
17. Croney D and Watkins LH. "Heavy Vehicles - Research Aspects" Journal of the Institution of Highway Engineers Reprint July (1974).
18. RTAC. "Vehicle Weights and Dimensions Study" Technical Steering Committee Report, Roads and Transportation Association of Canada (1986).
19. Hajek J, Kennepohl G and Billing J. "Applications of Weight-In-Motion Data in Transportation Planning" PAV-92-01, Ontario Ministry of Transportation (1992).
20. AASHTO. "Standard Specifications for Highway Bridges" 15th Edition American Association of State Highway and Transportation Officials, Washington (1992).
21. MTO. "Ontario Highway Bridge Design Guide" Third Edition Ontario Ministry of Transportation (1991).
22. MTO. "Vehicle Dimensions and Weight Limits in Ontario" Revised May 1986, Ontario Ministry of Transportation (1987).
23. Hutchinson BG, Rillet LR, Green R, and Haas RCG. "Axle Load Shifts During Truck Braking and Their Implications for Bridge and Pavement Design" Canadian Journal of Civil Engineering 16, 113-118 (1989).
24. Provincial Auditor. "Quality and Standards Activity, Ministry of Transportation" 1995 Annual Report, Office of the Ontario Provincial Auditor (1995).
25. MTO. "Pavement Design and Rehabilitation Manual" Ontario Ministry of Transportation (1990).
26. Carrick JA, Fraser B, Hein D, Emery J. "Pavement Performance and Life-Cycle Cost Evaluation of a Polymer-Modified Asphalt Cement" Proceedings Canadian Technical Asphalt Association 41 445-463 (1996).