APPENDIX C UNCERTAINTY PROPAGATION IN BOSTON FOUR-STEP TRANSPORT MODEL

Appendix C presents how uncertainty (model and behavior) propagates through the four-step model developed for Boston Metropolitan Area. We first define the uncertainty type and scenarios for a sub-model, and then run the full four-step model iterations to convergence. We evaluate the impact of uncertainty from one model on its subsequent steps, including the final impact on traffic and transit assignment.

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1 Uncertainty in Vehicle Ownership Model

1.1 Uncertainty Scenarios

We specified 5 scenarios for vehicle ownership model (Table 1–1).

Table 1–1 Uncertainty Scenarios for Vehicle Ownership Model

	Source of Uncertainty	Descriptions
SC_base	Baseline	
SC_high0	Sampling uncertainty	Parameters that generate 95-percentile 0-veh share
SC_low0	Sampling uncertainty	Parameters that generate 5-percentile 0-veh share
SC_noBE	Model uncertainty	No built environment variables
SC_90to10	Behavior uncertainty	1990 model parameters applied to 2010 population

The base-line model applies the VO model estimated from the 2010 Massachusetts Travel Survey (MTS). Its model structure is logit. Its utility specification includes socio-demographic, transit accessibility, and built environment variables. When applied to the four-step model, the expected values of the coefficients are used.

Variations in *model specification* is a source of model uncertainty. We consider 7 specifications, and selected two scenarios, *SC_base* and *SC_noBE*, for uncertainty propagation analysis in the four-step model. Compared to SC_base, SC_noBE does not have built environment (BE) variables: the accessibility ratio (transit accessibility/auto accessibility), distance to CBD, the squared distance to CBD, log of population density, and log of job-to-worker ratio in a TAZ. We compare the two scenarios to assess the uncertainty in outputs due to omitting BE variables.

Model estimation inherently has sampling uncertainty, since the parameters are estimated based on sample data. We first run 1000 simulations for VO model only, by randomly sampling from the joint distribution of the model parameters. Then we select out the critical scenarios – the sets of parameters that produce the 5 percentile and 95 percentile of the 1000 simulated outputs. We choose the predicted 0-vehicle households as the criteria for parameter selection,

because the 0-vehicle households are the most uncertain (with the highest coefficient of variation (CV)) (Table 1–2).

The impact of behavior uncertainty is assessed through transferring the 1990 VO parameters to the VO model in the 2010 four-step model. This scenario is called SC_90to10. It represents the circumstance when we do not know how people's vehicle ownership preferences evolve over time, and make forecast for 20 years later.

Table 1–2 Summary of 1000 VO Simulations

Predicted households by vehicles	Mean	S.D.	CV	Confidence Interval		2010 CTPP[1]
V0	202,332	8,907	**0.044**	184,776	219,638	226,034
V1	555,393	11,338	0.020	532,626	576,818	594,736
V2	628,757	9,123	0.015	610,469	646,301	619,171
V3	295,556	6,822	0.023	282,281	309,478	242,097

Table 1–3 Percentiles of Predicted 0-vehicle Households from 1000 Simulations

Percentile	5%	25%	50%	75%	95%
Predicted 0-veh HH	187,471	196,427	202,487	208,415	216,476
Relative to median	0.93	0.97	1.00	1.03	1.07
Simulation No[2].(1-1000)	314	508	24	772	437

1.2 Propagation of Uncertainty from Vehicle Ownership Model

We run each of the scenarios specified above throughout the Boston four-step model, and compare their outputs for each stage of the four-step model. We find that among the five scenarios, behavior uncertainty (SC_90to10) causes the largest discrepancy in VO forecast. Applying the 1990 model parameters to 2010, 0-vehicle and 3-vehicle households are under-predicted; while 1-vehicle and 2-vehicle households are greatly over-predicted.

We can see among the five scenarios (Table 1–4), behavior uncertainty (SC_90to10) causes the largest discrepancy in VO forecast. Applying the 1990 model parameters to 2010, 0-vehicle and 3-vehicle households are under-predicted; while 1-vehicle and 2-vehicle households are greatly over-predicted.

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1 Note that the population data 2010 CTPP is also based on survey with various expansion and imputation employed. See http://www.fhwa.dot.gov/planning/census_issues/ctpp/faq/ ideally, the confidence interval of the prediction should be compared to the observed confidence interval from CTPP.

2 Random seed=7

Table 1–4 Summary of Vehicle Ownership Prediction by the 5 Scenarios

	SC_base		SC_low0		SC_high0		SC_noBE		SC_90to10	
	Counts	%	Counts	%	Counts	%	Counts	%	Counts	%
0-veh	201957	12.0	187471	11.1	216475	12.9	198397	11.8	129925	7.7
1-veh	555660	33.0	572046	34.0	554974	33.0	556206	33.1	617208	36.7
2-veh	629302	37.4	628124	37.3	617001	36.7	629341	37.4	711025	42.3
3-veh	295663	17.6	294942	17.5	294131	17.5	298637	17.7	224424	13.3
Total	1682584	100.0	1682584	100	1682584	100	1682584	100	1682584	100

1.3 Impact on Trip Generation

All persons are divided into Choice and Captive group based on the vehicle ownership status of their households. If a household has no car, all members of that household are Captive traveler; otherwise, they are Choice riders.

Home-based-work (HBW) trip generation is based on individual worker's HBW trip rates. Since uncertainty in VO models affect the predicted share of 0-vehicle households, it also influences the number of trips by choice (P_HBW_CHO) vs. by captive workers (P_HBW_CAP), though the total HBW trips are constant given the same total number of workers. We observe that sampling uncertainty causes -15.7% to 11.2% discrepancy from the baseline, in terms of the predicted HBW trips for captives. Behavior uncertainty causes 32% underestimation of HBW trips for captives (Table 1–5).

Table 1–5 HBW Trip Production Results of 5 VO scenarios.

	SC_Base	**SC_low0**	**Diff**	**SC_high0**	**Diff**	**SC_noBE**	**Diff**	**SC_90to10**	**Diff**
P_HBW_CHO									
Earn1	679,033	686,888	1.2%	672,077	-1.0%	682,480	0.5%	696,431	2.6%
Earn2	746,677	752,077	0.7%	742,574	-0.5%	749,300	0.4%	758,447	1.6%
Earn3	552,362	555,933	0.6%	550,771	-0.3%	553,375	0.2%	558,355	1.1%
Earn4	285,020	286,913	0.7%	284,005	-0.4%	285,129	0.0%	288,259	1.1%
Earn5	291,738	293,383	0.6%	290,790	-0.3%	291,757	0.0%	294,884	1.1%
Total	2,554,830	2,575,194	0.8%	2,540,217	-0.6%	2,562,041	0.3%	2,596,376	1.6%

P_HBW_CAP									
Earn1	61,423	53,568	-12.8%	68,378	11.3%	57,976	-5.6%	44,024	-28.3%
Earn2	38,349	32,949	-14.1%	42,452	10.7%	35,726	-6.8%	26,579	-30.7%
Earn3	17,613	14,042	-20.3%	19,203	9.0%	16,600	-5.8%	11,620	-34.0%
Earn4	6,821	4,928	-27.8%	7,836	*14.9%*	6,712	-1.6%	3,582	*-47.5%*
Earn5	5,689	4,045	-28.9%	6,638	*16.7%*	5,671	-0.3%	2,544	*-55.3%*
Total	129,895	109,531	-15.7%	144,508	11.2%	122,684	-5.6%	88,349	-32.0%
P_HBW Total	2,684,725	2,684,725		2,684,725		2,684,725		2,684,725	

For other trip purposes, the impact of VO uncertainty on trip generation step is trivial, because trip generation for non-HBW trips is based on the trip rates for 56 household types, which is independent from household vehicle ownership.

Table 1–6 Trip Production Results of 5 VO scenarios for Other Trip Purposes

	SC_base	SC_lowV0	SC_highV0	SC_noBE	SC_90to10
HBSC	938,961	938,798	942,636	934,057	931,403
HBPUDO	1,352,788	1,354,237	1,351,472	1,350,174	1,392,008
HBSH	1,475,053	1,476,584	1,472,096	1,477,776	1,470,599
HBBPB	1,485,402	1,489,046	1,484,374	1,485,280	1,461,439
HBSO	765,194	766,956	763,640	765,680	768,106
HBEAT	583,788	585,022	582,505	584,927	581,651
HBREC	1,155,633	1,154,799	1,153,321	1,155,619	1,169,567
HBO	72,793	72,977	72,559	72,619	72,589
HBOA	4,062,810	4,068,800	4,056,399	4,064,125	4,053,352
NHBW	1,422,591	1,423,115	1,420,851	1,424,106	1,433,885
NHBO	2,526,583	2,533,052	2,518,661	2,526,690	2,534,373

1.4 Impact on Mode Choice

Table 1–7 shows the predicted HBW mode shares for the 5 VO scenarios. There are two key observations. First, the mode split results for non-work trip purposes (HBSHOP, HBO, NHBO) are more sensitive to the uncertainty in VO step. This is probably because the relationship between mode choice and vehicle ownership is stronger for non-work trip purposes than that for work-related trip purposes.

Secondly, behavior uncertainty in VO model produces the largest discrepancy from the baseline at the mode choice stage. SC_90to10 persistently over-predicts trips by SOV, APAX, and DAT; and under-estimates trips by WAT and WALK. This is consistent with the fact that SC_90to10 under-predicts 0-vehicle households and over-predicts 2-vehicle households.

Table 1–7 Predicted Mode Shares of HBW Trips for 5 VO Scenarios

	SC_base	SC_lowV0	SC_highV0	SC_noBE	SC_90to10
SOV	1,993,685	2,001,361	1,982,830	2,000,503	2,024,354
APAX	117,980	118,371	118,580	120,157	122,395
WAT	216,298	218,376	218,787	210,898	210,943
DAT	117,049	117,530	117,240	118,026	118,468
WALK	239,711	229,085	247,286	235,138	208,562
Total	2,684,723	2,684,723	2,684,723	2,684,722	2,684,722
Compared to base					
SOV	--	0.4%	-0.5%	0.3%	1.5%
APAX	--	0.3%	0.5%	1.8%	3.7%
WAT	--	1.0%	1.2%	-2.5%	-2.5%
DAT	--	0.4%	0.2%	0.8%	1.2%
WALK	--	-4.4%	3.2%	-1.9%	-13.0%

Table 1–8 Predicted Mode Shares of HBSHOP Trips for 5 VO Scenarios

	SC_base	SC_lowV0	SC_highV0	SC_noBE	SC_90to10
SOV	727,770	733,585	722,076	721,229	739,899
APAX	226,283	226,774	225,918	224,400	230,301
WAT	46,029	44,818	47,648	44,080	41,908
DAT	6,504	6,565	6,485	6,296	6,852
WALK	468,464	464,839	469,966	481,769	451,637
Compared to base					

SOV	--	0.8%	-0.8%	-0.9%	1.7%
APAX	--	0.2%	-0.2%	-0.8%	1.8%
WAT	--	-2.6%	3.5%	-4.2%	-9.0%
DAT	--	0.9%	-0.3%	-3.2%	5.4%
WALK	--	-0.8%	0.3%	2.8%	-3.6%

Table 1–9 Predicted Mode Shares of HBO Trips for 5 VO Scenarios

	SC_base	SC_lowV0	SC_highV0	SC_noBE	SC_90to10
SOV	2,578,442	2,592,462	2,562,240	2,557,892	2,622,203
APAX	955,001	957,228	953,025	953,723	986,791
WAT	139,247	136,468	144,806	132,349	124,543
DAT	38,685	39,043	38,567	38,006	40,358
WALK	1,704,221	1,697,834	1,709,232	1,732,326	1,671,463
TOTAL	5,415,596	5,423,035	5,407,870	5,414,296	5,445,358
Compared to base:					
SOV		0.5%	-0.6%	-0.8%	1.7%
APAX		0.2%	-0.2%	-0.1%	3.3%
WAT		-2.0%	4.0%	-5.0%	-10.6%
DAT		0.9%	-0.3%	-1.8%	4.3%
WALK		-0.4%	0.3%	1.6%	-1.9%

Table 1–10 Predicted Mode Shares of NHBW Trips for 5 VO Scenarios

	SC_base	SC_lowV0	SC_highV0	SC_noBE	SC_90to10
SOV	891,568	896,016	887,789	888,472	909,899
APAX	44,012	43,732	44,230	44,096	43,931
WAT	28,911	28,572	29,442	28,348	28,005
DAT	10,752	10,837	10,716	10,715	11,094
WALK	447,345	443,956	448,673	452,473	440,953
TOTAL	1,422,588	1,423,113	1,420,850	1,424,104	1,433,882
Compared to base:					
SOV		0.5%	-0.4%	-0.3%	2.1%
APAX		-0.6%	0.5%	0.2%	-0.2%
WAT		-1.2%	1.8%	-1.9%	-3.1%
DAT		0.8%	-0.3%	-0.3%	3.2%
WALK		-0.8%	0.3%	1.1%	-1.4%

Table 1–11 Predicted Mode Shares of NHBO Trips for 5 VO Scenarios

	SC_base	SC_lowV0	SC_highV0	SC_noBE	SC_90to10
SOV	1,192,192	1,201,142	1,183,346	1,177,752	1,206,563
APAX	487,884	489,714	486,150	487,857	507,024
WAT	50,989	49,832	53,008	48,117	44,804
DAT	6,059	6,126	6,035	5,984	6,289
WALK	789,457	786,235	790,118	806,977	769,691

TOTAL	2,526,581	2,533,049	2,518,657	2,526,687	2,534,371
Compared to base:					
SOV		0.8%	-0.7%	-1.2%	1.2%
APAX		0.4%	-0.4%	0.0%	3.9%
WAT		-2.3%	4.0%	-5.6%	-12.1%
DAT		1.1%	-0.4%	-1.2%	3.8%
WALK		-0.4%	0.1%	2.2%	-2.5%

1.5 Impact on Traffic and Transit Assignment

Table 1–12 Predicted VMT and VHT for the 5 VO Scenarios

	SC_base	SC_lowV0	SC_highV0	SC_noBE	SC_90to10
VMT	84,826,543	85,237,833	84,533,237	83,690,436	85,123,361
(diff)		0.5%	-0.3%	-1.3%	0.3%
VHT	2,307,072	2,320,571	2,297,041	2,277,054	2,323,233
(diff)		0.6%	-0.4%	-1.3%	0.7%

Table 1–13 Predicted Transit Ridership for the 5 VO Scenarios

	SC_base	**SC_lowV0**	**SC_highV0**	**SC_noBE**	**SC_90to10**
Bus	503,326	498,201	516,552	463,988	461,307
Silver line	29,400	29,218	30,206	29,279	28,542
Red line	262,765	264,170	265,114	261,390	259,975
Orange line	237,027	239,210	237,749	236,321	238,469
Blue line	63,571	64,033	63,843	64,158	62,892
Green line	234,447	234,929	237,270	235,100	232,341
Commuter Rail	146,547	147,628	146,737	145,686	149,639
Compared to base		**SC_lowV0**	**SC_highV0**	**SC_noBE**	**SC_90to10**
Bus		-1%	3%	**-8%**	**-8%**
Silver line		-1%	3%	0%	-3%
Red line		1%	1%	-1%	-1%
Orange line		1%	0%	0%	1%
Blue line		1%	0%	1%	-1%
Green line		0%	1%	0%	-1%

Commuter Rail		1%	0%	-1%	2%

2 Uncertainty in Trip Generation

2.1 TG Scenarios

- SC_low: 5-percentile of the trip rate sampling distribution
- SC_high: 95-percentile of the trip rate sampling distribution
- SC_90to10: 1990 trip rates applied to 2010

2.2 Predicted Trip Generation

Table 2–1 HBW Trip Production Results for 4 TG Scenarios

	SC_base	SC_low	SC_high	SC_90to10
HBW per worker	**1.32**	**1.30**	**1.33**	**1.51**
Work at home rate	**[0.049, 0.0291, 0.0295, 0.0417, 0.0586]**			**[0.042, 0.0142, 0.012, 0.0149, 0.024]**
Earn1	740,456	730,626	748,049	860,559
Earn2	785,026	774,605	793,076	919,590
Earn3	569,975	562,408	575,820	669,443
Earn4	291,841	287,966	294,834	346,115
Earn5	297,427	293,479	300,478	355,757
Total	2,684,725	2,649,085	2,712,256	3,151,464
Diff from base		**-1.3%**	**1.0%**	**17.4%**

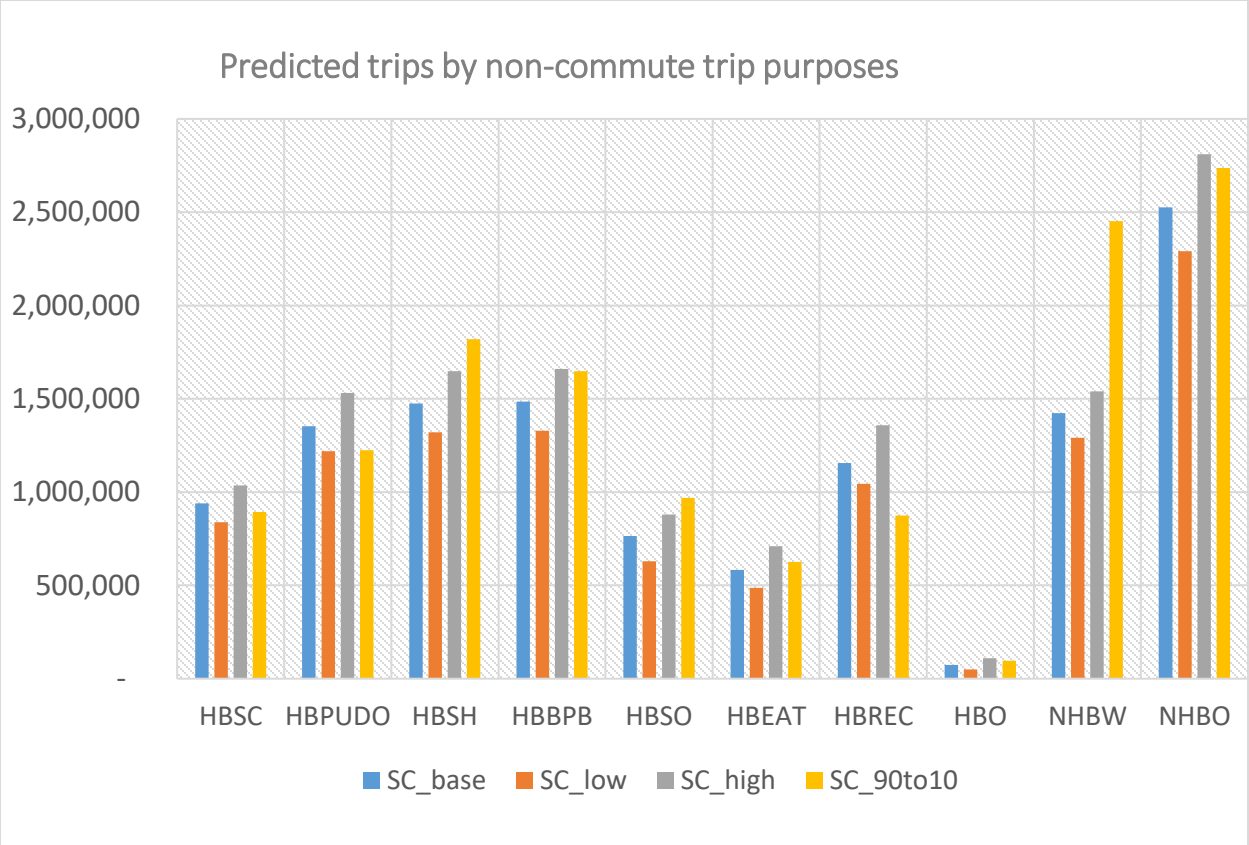

Figure 2-1 Predicted Trips for Other Trip Purposes for TG scenarios

Table 2–2 Predicted Trips Compared to Base Scenario

	SC_low	SC_high	SC_90to10
HBSC	-11%	10%	-5%
HBPUDO	-10%	13%	-9%
HBSH	-10%	12%	23%
HBBPB	-11%	12%	11%
HBSO	-18%	15%	27%
HBEAT	-17%	22%	7%
HBREC	-10%	18%	-24%
HBO	-33%	50%	32%
NHBW	-9%	8%	72%
NHBO	-9%	11%	8%

2.3 Impact on Traffic and Transit Assignment

Table 2–3 VMT and VHT Generated by the 4 TG Scenarios

	Total VMT				Total VHT			
	SC_base	SC_low	SC_high	SC_90to10	SC_base	SC_low	SC_high	SC_90to10
Expressways	47,910,235	45,739,023	50,734,157	54,163,172	880,907	838,123	940,336	1,028,533
Main Arterials	4,575,151	4,364,070	4,853,723	5,115,878	125,786	118,944	135,145	145,549
Minor Arterials	15,363,804	14,436,722	16,603,387	17,976,887	563,335	526,654	611,712	670,125
Main Distributors	11,408,831	10,646,954	12,447,599	13,575,919	466,139	434,605	509,301	558,395
Minor Distributors	1,531,897	1,466,257	1,639,421	1,738,344	66,600	64,410	71,803	76,878
Local streets	4,036,625	3,746,566	4,459,649	4,862,342	204,305	189,275	226,235	247,765
Total	**84,826,543**	**80,399,592**	**90,737,936**	**97,432,542**	**2,307,072**	**2,172,011**	**2,494,532**	**2,727,245**
Expressways		-5%	6%	13%		-5%	7%	17%
Main Arterials		-5%	6%	12%		-5%	7%	16%
Minor Arterials		-6%	8%	17%		-7%	9%	19%
Main Distributors		-7%	9%	19%		-7%	9%	20%
Minor Distributors		-4%	7%	13%		-3%	8%	15%
Local streets		-7%	10%	20%		-7%	11%	21%
Total		**-5%**	**7%**	**15%**		**-6%**	**8%**	**18%**

Table 2–4 Transit Ridership Generated by the 4 TG Scenarios

	SC_base	SC_low	SC_high	SC_90to10
Bus	503,326	474,406	565,576	586,560
Silver line	29,400	27,689	33,553	34,969
Red	262,765	250,669	284,860	302,320
Orange line	237,027	226,004	258,013	272,341
Blue line	63,571	60,798	69,895	73,165
Green line	234,447	222,895	254,809	268,897
Commuter Rail	146,547	142,142	153,074	162,717

Total	**1,477,083**	**1,404,604**	**1,619,780**	**1,700,970**
	SC_base	SC_low	SC_high	SC_90to10
Bus		-6%	12%	17%
Silver line		-6%	14%	19%
Red		-5%	8%	15%
Orange line		-5%	9%	15%
Blue line		-4%	10%	15%
Green line		-5%	9%	15%
Commuter Rail		-3%	4%	11%
Total		**-5%**	**10%**	**15%**

Table 2–5 Summary of the Impact of the TG Uncertainty Scenarios on Traffic Assignment

	SC_low	**SC_high**	**SC_90to10**
Total trips	-9%	11%	14%
Total VMT	**-5%**	**7%**	**15%**
Total VHT	**-6%**	**8%**	**18%**
AM VMT	-3%	2%	17%
AM VHT	-3%	3%	21%
MD VMT	-6%	9%	22%
MD VHT	-7%	10%	26%
Transit Ridership	**-5%**	**10%**	**15%**

3 Uncertainty in Mode Choice

3.1 Mode Choice Scenarios

- Base
- behav_90to10 (behavior uncertainty)
- params_highSOV (parameter uncertainty)
- params_lowSOV (parameter uncertainty)

3.2 Predicted Mode Shares by Mode

Table 3–1 Predicted HBW Mode Shares by 5 MC Scenarios

HBW	base10	lowSOV	highSOV	90to10	Observed
SOV	74.6%	74.4%	75.0%	70.4%	**71.9%**
APAX	4.4%	4.9%	4.4%	9.3%	**9.1%**
WAT	7.4%	7.7%	6.9%	6.0%	**13.5%**
DAT	4.2%	3.8%	4.3%	4.5%	
WALK	9.3%	9.2%	9.3%	9.8%	**5.5%**

Table 3–2 Predicted HBSHOP Mode Shares by 5 MC Scenarios

HBSHOP	base10	lowSOV	highSOV	90to10	Observed
SOV	49.3%	48.7%	50.3%	34.8%	**67.2%**
APAX	15.4%	15.4%	14.3%	30.6%	**18.9%**
WAT	2.9%	3.1%	3.0%	1.9%	**5.7%**
DAT	0.4%	0.7%	0.5%	0.3%	**0.1%**
WALK	31.9%	32.1%	32.0%	32.3%	**8.2%**

Table 3–3 Predicted HBO Mode Shares by 5 MC Scenarios

HBO	base10	lowSOV	highSOV	90to10	Observed
SOV	47.6%	46.9%	48.2%	30.4%	64.2%
APAX	17.6%	18.2%	17.2%	35.9%	23.0%
WAT	2.4%	2.4%	2.4%	1.5%	5.8%
DAT	0.7%	0.8%	0.7%	0.6%	0.3%
WALK	31.6%	31.7%	31.6%	31.6%	6.6%

Table 3–4 Predicted NHBW Mode Shares by 5 MC Scenarios

NHBW	base10	lowSOV	highSOV	90to10	Observed
SOV	62.7%	62.0%	62.9%	52.2%	75.0%
APAX	3.1%	3.6%	2.9%	13.6%	4.2%
WAT	1.9%	1.9%	2.0%	1.4%	6.7%
DAT	0.7%	0.8%	0.7%	0.6%	0.7%
WALK	31.6%	31.7%	31.5%	32.3%	13.5%

Table 3–5 Predicted NHBO Mode Shares by 5 MC Scenarios

NHBO	base10	lowSOV	highSOV	90to10	Observed
SOV	47.1%	46.4%	47.7%	28.6%	**60.2%**
APAX	19.3%	20.1%	18.9%	36.6%	**26.1%**
WAT	1.9%	1.9%	1.9%	1.9%	**4.5%**
DAT	0.2%	0.3%	0.2%	1.2%	**0.1%**
WALK	31.4%	31.4%	31.3%	31.7%	**9.2%**

3.3 Impact on Traffic and Transit Assignment

Table 3–6 Differences in Predicted VMT from Base Scenario

	SC_lowSOV	**SC_highSOV**	**SC_90to10**
Expressways	-0.7%	0.6%	-21.1%
Main Arterials	-1.0%	0.7%	-19.8%
Minor Arterials	-1.0%	0.9%	-24.0%
Main Distributors	-1.1%	1.0%	-25.6%
Minor Distributors	-0.8%	0.8%	-21.2%
Local streets	-1.2%	1.2%	-26.7%
Total	-0.9%	0.8%	-22.4%

Table 3–7 Predicted Transit Ridership by MC Scenarios

					Compared to base		
	base10	**lowSOV**	**highSOV**	**90to10**	**lowSOV**	**highSOV**	**90to10**
Bus	458,200	471,895	445,721	337,836	3.0%	-2.7%	-26.3%
Silver line	27,817	27,775	27,176	20,497	-0.2%	-2.3%	-26.3%
Red	252,605	256,073	245,274	221,986	1.4%	-2.9%	-12.1%
Orange line	227,631	229,691	219,959	198,751	0.9%	-3.4%	-12.7%
Blue line	61,577	62,010	60,405	55,372	0.7%	-1.9%	-10.1%
Green line	227,266				0.3%	-2.9%	-12.8%

		227,846	220,562	198,130			
Commuter Rail	142,870	143,152	141,121	139,101	0.2%	-1.2%	-2.6%
Total	***1,397,967***	***1,418,443***	***1,360,219***	***1,171,674***	***1.5%***	***-4.1%***	***-13.9%***