Technical White Paper

Application of Detailed Interchange Analysis to Top Freight Bottlenecks: Methods, Results, and Road Map for Future Research

prepared for

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1. INTRODUCTION

1.1 Background

Freight bottlenecks are an increasing problem today because they delay large numbers of truck freight shipments. They will become increasingly problematic in the future as the U.S. economy grows and generates more demand for truck freight shipments. If the U.S. economy grows at a conservative annual rate of 2.5 to 3 percent over the next 20 years, domestic freight tonnage will almost double and the volume of freight moving through the largest international gateways may triple or quadruple. Without new strategies to increase capacity, congestion at highway freight bottlenecks may impose an unacceptably high cost on the nation's economy and productivity.

The Texas Transportation Institute's (TTI) 2004 Urban Mobility Report estimates that the cost of congestion in 75 of the Nation's large urban areas in 2001 was $69.5 billion. Corresponding to that dollar loss is 3.5 billion hours of delay and 5.7 billion gallons of excess fuel consumed. However, the TTI methodology is based on analyzing mainline segments of highway rather than specific bottlenecks.

The Federal Highway Administration (FHWA) together with the Texas Transportation Institute currently uses the Highway Performance Monitoring System (HPMS) and the National Bridge Inventory (NBI) to estimate congestion. Neither HPMS nor NBI adequately reflect the influence of interchanges on highway capacity. The HPMS contains data on the through-lane capacity but does not account for the reduced capacity caused by weaving and merging movements at interchanges. In fact, interchanges are not even explicitly identified in the HPMS. The NBI does contain data on bridges located at interchanges but it does not include detailed information about the interchanges and NBI does not treat interchange bridges separately from other bridges. In short, the two data systems and the models based on those systems (Highway Economic Requirements System and TTI's congestion model) do not support the estimation of interchange congestion impacts. Further, congestion often extends well beyond the locus of the interchange.

This data/methodology gap was discovered as part of the *An Initial Assessment of Freight Bottlenecks on Highways*[1]. Using a Bottleneck Delay Estimator developed by Cambridge Systematics (CS) for the American Highway Users Alliance[2], CS developed preliminary estimates of the truck hours of delay on the "critical leg" of each interchange based on information from the HPMS database.

This previous analysis of freight (highway) bottlenecks shows a highly skewed distribution of bottlenecks -- primarily interchanges on urban Interstate highways -- accounting for 50 percent of

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[1] Cambridge Systematics, Inc., *An Initial Assessment of Freight Bottlenecks on Highways*, prepared for Federal Highway Administration Office of Transportation Policy Studies, October 2005.

[2] American Highway Users Alliance, *Unclogging America's Arteries: Effective Relief for Highway Bottlenecks*, 2004, http://www.highways.org/pdfs/bottleneck2004.pdf

the delay hours. However, the truck delay estimates are incomplete because the HPMS database does not have sufficiently detailed data to calculate (1) the delay effects of merge and weave areas at the interchanges, and (2) delays accrued by trucks in the other legs of the interchanges. *The objective of this project is to conduct a feasibility study to determine how to model the delay associated with highway interchanges and then develop an interchange bottleneck delay estimator that can be applied to the national list of significant highway interchange bottlenecks.*

1.2 Previous Work

This study builds on the work performed in Reference (1). In that study, truck bottlenecks were defined by a combination of three features: the type of constraint, the type of roadway, and the type of freight route. Table 1.1 shows how these three features were combined.

Table 1.1 Previously Estimated Truck-Hours of Delay by Bottleneck Type

Bottleneck Type			**National Annual Truck Hours of Delay, 2004 (Estimated)**
Constraint	**Roadway**	**Freight Route**	
Interchange	Freeway	Urban Freight Corridor	123,895,000
			Subtotal **123,895,000***
Steep Grade	Arterial	Intercity Freight Corridor	40,647,000
Steep Grade	Freeway	Intercity Freight Corridor	23,260,000
Steep Grade	Arterial	Urban Freight Corridor	1,509,000
Steep Grade	Arterial	Truck Access Route	303,000
			Subtotal **65,718,000‡**
Signalized Intersection	Arterial	Urban Freight Corridor	24,977,000
Signalized Intersection	Arterial	Intercity Freight Corridor	11,148,000
Signalized Intersection	Arterial	Truck Access Route	6,521,000
Signalized Intersection	Arterial	Intermodal Connector	468,000
			Subtotal **43,113,000‡**
Lane Drop	Freeway	Intercity Freight Corridor	5,221,000
Lane Drop	Arterial	Intercity Freight Corridor	3,694,000
Lane Drop	Arterial	Urban Freight Corridor	1,665,000
Lane Drop	Arterial	Truck Access Route	41,000
Lane Drop	Arterial	Intermodal Connector	3,000
			Subtotal **10,622,000‡**
			Total 243,032,000

Source: Reference (1)

One of the major results of this study verified previous notions about truck bottlenecks – that urban interchanges heavily used by weekday commuters represent the overwhelming source of delay for trucks. However, the methodology used to estimate delay and perform the rankings is a very simple scanning level of analysis. Given the importance of these types of bottlenecks, a more rigorous delay analysis was decided upon and the results are presented herein.

A study performed for the Ohio Department of Transportation[3] expanded on the bottleneck analysis approach used in both the AHUA and previous FHWA studies. On freeways, the AHUA study found that the predominant type of bottleneck was freeway-to-freeway interchanges. Lane-drop bottlenecks were far less common and interchanges with surface streets produced significantly less delay than freeway-to-freeway interchanges. The AHUA methodology (used also in the previous FHWA bottleneck study) is based on identifying the "critical leg" of a freeway-to-freeway interchange (i.e., one of the two intersecting highways for the interchange) and assumes that all interchange delay is attributable to that leg. (Lane-drop and freeway-to-surface-street bottlenecks do not need this assumption since there is only one freeway "leg" present. In the AHUA approach, delay is estimated using a set of equations developed from a queuing-based model; these are the same equations that are in FHWA's Highway Economic Requirements (HERS) model. This provides a good first-cut for identifying bottlenecks but delay is highly dependent on the actual interchange configurations (roadway geometry) at each location. For the Ohio work, the methodology was extended by:

- Applying the actual queuing procedure (rather than default equations) on a ramp-by-ramp basis at each bottleneck. Detailed interchange configurations were available from ODOT's straight line diagrams.

- Estimating truck delay from actual truck counts at the bottlenecks (rather than aggregate AADT and truck percentage values).

The Ohio methodology is therefore more closely aligned with an operational-level analysis similar to those in the *Highway Capacity Manual.* It identifies specific merge points within each interchange that are the causes of delay (usually, not all merge points are problems) rather than using the planning-level notion of a "critical leg". Figure 1.1 details the Ohio methodology for determining truck demand at each bottleneck.

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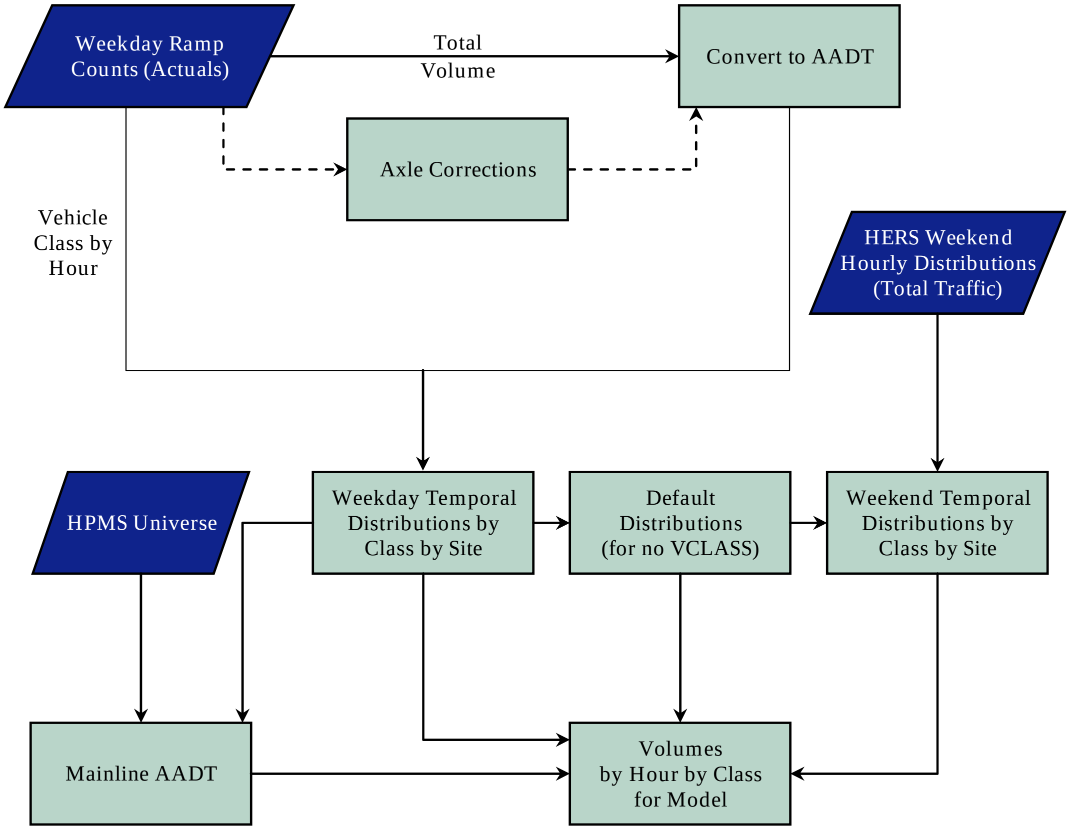
[3] Maring, Gary, Margiotta, Rich, Hodge, Daniel, and Beagan, Dan, *Ohio Freight Mobility,* prepared for Ohio Department of Transportation ,Office of Research and Development, December 30, 2005.

Figure 1.1. Traffic Data Preparation in the Ohio Study[3]



2. METHODOLOGY

The approach taken for the present study was intermediate in complexity and data requirements between the AHUA and Ohio methodologies. The specifics of the methodology follow.

2.1 Physical Characteristics of Interchanges

Interchange configurations and geometrics were obtained using the satellite-based photos available from GoogleEarth.[4] Figure 2.1 shows an example of the photos available; Appendix A[5] shows the photos for all the interchanges studied. Figure 2.1 is still at a relatively low resolution rate – more detailed resolutions are available that allow determining the number of lanes at specific points. (Indeed, even individual vehicles can be ascertained, even down to telling if they are a car, truck, or large truck!)

For each interchange, the key merge points *where traffic is moving away from the center of the interchange* were identified. At each merge point, the number of entering and exiting lanes was noted. If there was a change in the number of exiting lanes within 1,500 feet of the interchange, this too was noted. The capacity of each merge juncture was determined by the minimum of either the number of exiting lanes or the number of lanes 1,500 feet downstream. Table 2.1 shows the basic information used at each merge juncture. The interchange configuration information used in this study is therefore as detailed as that used in the Ohio study.

As shown in Appendix A, the design (ramp configuration) of many of the interchanges is extremely complex. For that reason, some of the interchanges exhibit multiple ramp merges for a particular “exit” (i.e., travel direction away from the interchange).

2.2 Traffic Volumes at Interchanges

The detailed traffic data available for the Ohio study were not available for this study. The scope of this study did not allow for the contact of other DOTs and assembly of the data. Further, it is not known if other DOTs maintain counts, especially vehicle classification counts, on freeway-to-freeway ramps. Therefore, a simpler method was developed. AADTs for all the approaches of the interchanges were identified from the HPMS Universe data using the LRS Beginning and Ending Points. Because the HPMS Universe data provides continuous coverage of highway segments, there were no gaps the highway segments used for this analysis. Identifying which HPMS segments were located immediately prior to the interchange involved some judgment, with the LRS information being used to get close to the interchange, then looking for large changes in AADTs indicating that merging and diverging traffic flow was occurring. Once AADTs (two-way) for each approach were identified, it was assumed that the directional AADT was half of the total AADT. Turning movements were then synthetically derived using the

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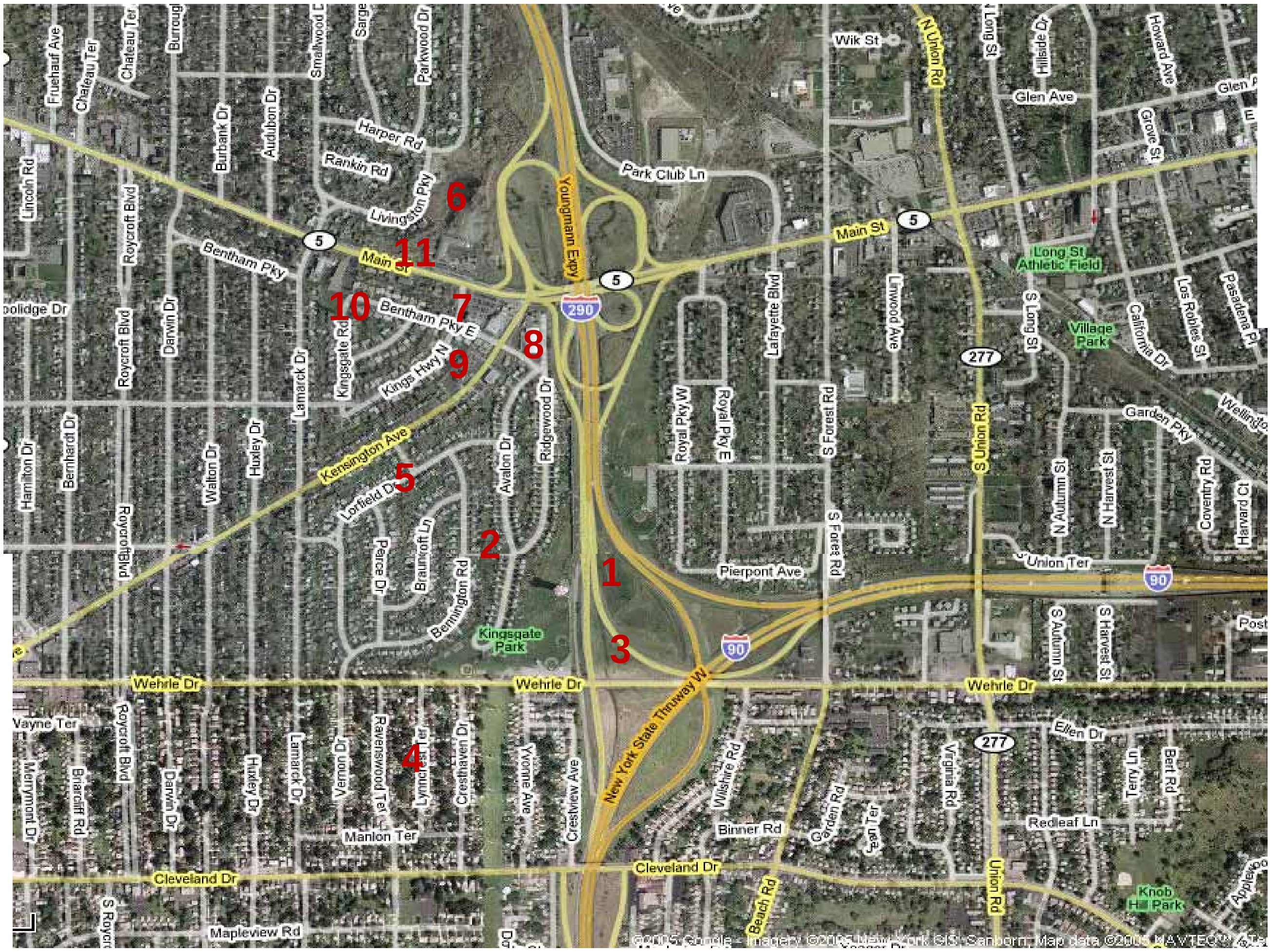
[4] http://earth.google.com/

[5] Appendix A is available as a separate document due to its large file size.

Figure 2.1 I-90/I-290 Interchange, Buffalo, NY



1. 3-lane corridor, with 1 lane splitting off as the ramp. Ramp later expands to 2 lanes.
2. 90 WB to 290 NB 2-lane ramp adds to 90 EB / NB to 290 NB 2-lane ramp, becomes 4 lanes. Becomes 3 lanes shortly downstream.
3. 2-lane ramp becomes 1-lane and merges onto 2-lane corridor. Corridor expands to 5 lanes near what seems to be a toll plaza further downstream.
4. 3-lane ramp becomes 2-lane, adds to 90 WB / SB, becomes 4 lanes. Constricts to 3 lanes downstream.
5. 1-lane onramp barrier-separated from 290 – later joins the ramp to 90 WB / SB.
6. 1-lane ramp merges onto 3-lane corridor.
7. 1-lane ramp becomes aux lane on a 2-lane highway.
8. 1-lane ramp merges onto 2-lane highway.
9. 1-lane ramp merges onto 3-lane corridor.
10. 1-lane ramp merges onto 2-lane highway.
11. 1-lane ramp becomes aux lane on a 3-lane corridor.

Table 2.1 Basic Characteristics of Interchanges Used in the Analysis

			Ramp-to-Ramp		Ramp-to-Mainline	
BOTTLENECK NAME	**Exiting Direction**	**Pct. Trucks**	**Dir AADT**	**No. Lanes**	**Dir AADT**	**No. Lanes**
I-90 at I-290 in Buffalo	NB	0.24	67614	4	67614	4
	SB	0.10	65871	2	65871	3
	EB	0.10			67614	2
	NB	0.24	67614	4	67614	4
I-17 at I-10 in Phoenix	EB	0.13	51516	2	121130	6
	WB	0.13	51516	2	121130	6
	NB	0.11			61499	4
	SB	0.11	73016	3	104499	5
I-285 at I-85 in Atlanta	EB	0.13	59836		126020	6
	EB	0.13	35100	2		
	EB	0.13	60836	4	127020	7
	WB	0.13	68251	4	134435	6
	NB	0.13	39896	3		
	NB	0.13	73996	4	134495	6
	NB	0.13			133495	5
	SB	0.13	55091	4	115590	5
	SB	0.13	26736	2		
I-90/94 at I-290 in Chicago	EB	0.11	57278	2	102050	5
	EB	0.11			102050	4
	WB	0.11	34989	2		
	WB	0.11	58278	2	103050	4
	NB	0.05	46578	2	117300	4
	NB	0.05	46578	2	117301	4
	SB	0.05	67978	3	138700	5
	SB	0.05	67978	3	138700	5
I-15 at I-10 in Los Angeles	EB	0.20	58068	5	123000	5
	WB	0.20			117500	7
	WB	0.20	52568	5	117500	7
	NB	0.11	58068	4	105000	6
	SB	0.11	53068	5	100000	5
	SB	0.11			100000	5
I-90 at I-94 split in Chicago	NB	0.12			118750	4
	SB	0.12			23850	4
I-75 at I-285 in Atlanta	EB	0.13	19145	2		
	EB	0.13	49016	2	82795	7
	EB	0.13			81795	5
	WB	0.13	73382	2	107161	4
	NB	0.13	47651	4		
	NB	0.13	77522	4	175614	7
	SB	0.13	28730	2		
	SB	0.13	46875	3	144964	6

			Ramp-to-Ramp		Ramp-to-Mainline	
BOTTLENECK NAME	**Exiting Direction**	**Pct. Trucks**	**Dir AADT**	**No. Lanes**	**Dir AADT**	**No. Lanes**
SR-134 at SR-2 in Los Angeles	EB	0.03			121999	5
	WB	0.03			88615	5
	WB	0.03			109500	6
	NB	0.12	48972	2	72497	6
	NB	0.12	48975	2	72497	6
	SB	0.12			44159	4
	SB	0.12			59500	5
I-710 at I-105 in Los Angeles	EB	0.16	26466	6	75116	6
	EB	0.16			99000	6
	WB	0.16			109500	5
	WB	0.16	29966	4	78616	5
	NB	0.05	52850	2	113500	5
	NB	0.05	24884	2		
	SB	0.05	56350	3	117000	6
	SB	0.05	26466	2		
I-20 at I-285 in Atlanta	EB	0.14	39715	3	84335	5
	EB	0.14	39715	3	84335	5
	WB	0.14			63936	4
	WB	0.14			82285	4
	NB	0.10	37697	4	71199	6
	NB	0.10	37697	4	71199	6
	SB	0.10	39683	2	73185	4
	SB	0.10	39683	2	73185	4
I-80 at I-94 split in Chicago	EB	0.18	57364	2	66247	4
	WB	0.18	45191	2	50000	3
	NB	0.18			21364	2
	NB	0.18			30250	3
	SB	0.18			58450	2
	SB	0.18	30916	2	57450	2
SR-60 at I-605 in LA	EB	0.15	100740	4	131500	6
	WB	0.15	99740	4	130500	5
	NB	0.12	85236	6	116527	5
	NB	0.12			116527	5
	SB	0.12	85236	5	116527	6
I-55 at Pulaski in Chicago	EB	0.15	4734	1	89017	3
	WB	0.15	4734	1	89017	3
	NB	0.15			2634	2
	SB	0.15			2634	2
I-75 at I-85 in Atlanta	NB	0.07			144700	6
	SB	0.07			325000	12
I-93 at I-95 in Boston (South)	EB	0.14			75550	4
	WB	0.14			77896	3
	SB	0.14			77896	3
	SB	0.14			77896	3

			Ramp-to-Ramp		**Ramp-to-Mainline**	
BOTTLENECK NAME	**Exiting Direction**	**Pct. Trucks**	**Dir AADT**	**No. Lanes**	**Dir AADT**	**No. Lanes**
I-290 at I-355 in Chicago	EB	0.08			72600	4
	NB	0.08			94100	5
	SB	0.08			85100	3
I-405 at I-605 in LA	NB	0.15	157058	5	160000	6
	SB	0.15			2219	2
	EB	0.15	129933	7	131000	8
	WB	0.15	2219	1	132152	5
I-75 at I-74 in Cincinnati	WB	0.10	59000	3	0	4
	WB	0.10	0	3	0	4
	SB	0.12	0	2	89516	4
	NB	0.12	0	1	78000	3
I-880 at SR-238 in Oakland	EB	0.12	22471	3	42000	3
	SB	0.10			121000	5
	NB	0.10	101524	5	123000	5
SR-315 at I-70 in Columbus	EB	0.12	0	3	79557	4
	WB	0.12	26254	2	63646	4
	SB	0.12	52379	2	67279	4
	NB	0.12	24999	2	18775	3
I-93 at I-90 in Boston	EB	0.08			47737	2
	WB	0.08			55313	3
	SB	0.07			92192	4
	NB	0.07			93578	4
I-80 @ I-580 / I-880 Oakland, CA	NB	0.14	143500	4	143500	5
	NB	0.09	143500	4	143500	5
	WB	0.09			194947	7
	EB	0.09			55000	5
I-77 @I-277 in Charlotte, NC (South)	NB	0.17	10053	1	59445	4
	SB	0.17	21579	1	71209	3
	NB	0.17	2007	1		
	SB	0.17			58203	2
	EB	0.17			28946	4
	EB	0.17			17209	3

balancing procedure first identified in NCHRP 255 and in widespread use among travel demand modelers.[6] Turning movements were then assigned to each ramp.

Truck percents were obtained from two sources. First, for the dominant route in the interchange name (i.e., the first route number in the name), truck percents were obtained from the FAF-based assignments from Reference (1). For all other routes, truck percents were obtained from the HPMS Sample data.

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[6] Pedersen, N.J. and Samdahl, Don, NCHR Report 255, Highway Traffic Data for Urbanized Area Project Planning and Design, December 1982.

2.3 Delay Estimation

Background

This study uses the delay equations developed in a previous FHWA study[7] and subsequently adapted for use in the HERS model. A series of these equations were developed specifically to estimate the delay due to recurring bottlenecks. A brief history of the development of this methodology follows.

The equations were developed by using a simple queuing-based model. The procedure works as shown in Figure 2.2:

- The test link is assumed to have a bottleneck at the downstream end and that queuing will back upstream from there. The capacity of the link is assumed to be fixed at 2,400 passenger-cars-per-hour-per-lane (pcphpl).
- AADT/C levels from 1 to 18 are used. These represent the level of congestion. Since daily and peak period delays need to be computed, V/C is not a relevant indicator or overall congestion.
- The model considers traffic on an hourly basis. Hourly traffic distributions from a detailed study of urban traffic patterns[8] are used. Peak spreading is built into these equations: as congestion increases, demand is spread into hours around the traditional peak hours. The hourly demand volume for each run is selected by sampling from this distribution – in this way, the effect of day-to-day traffic variability is captured.
- If volume for an hour is greater than capacity, then a queue is built and carried over to successive hours until it dissipates.
- The procedure is repeated by sampling anew from the hourly traffic distributions. The resulting set of delay values were then used to fit equations.

Note that this method considers the effect of delay from the interaction of demand and physical capacity only (usually termed “recurring” delay). It does not include or estimate incident related delay.

The basis of the model is the definition of capacity. If a highway section has a reduced capacity from “normal” (e.g. , due to weaving or other geometric constraint), then this reduced capacity must be used in the application of this model. Essentially, it treats all bottlenecks the same – just with varying values of capacity. This assumption will miss some of the operational nuances of certain types of conditions (weaves) when flows are restricted but still above level of service F (forced flow); after breakdown occurs, then the queuing procedure probably captures the effects adequately.

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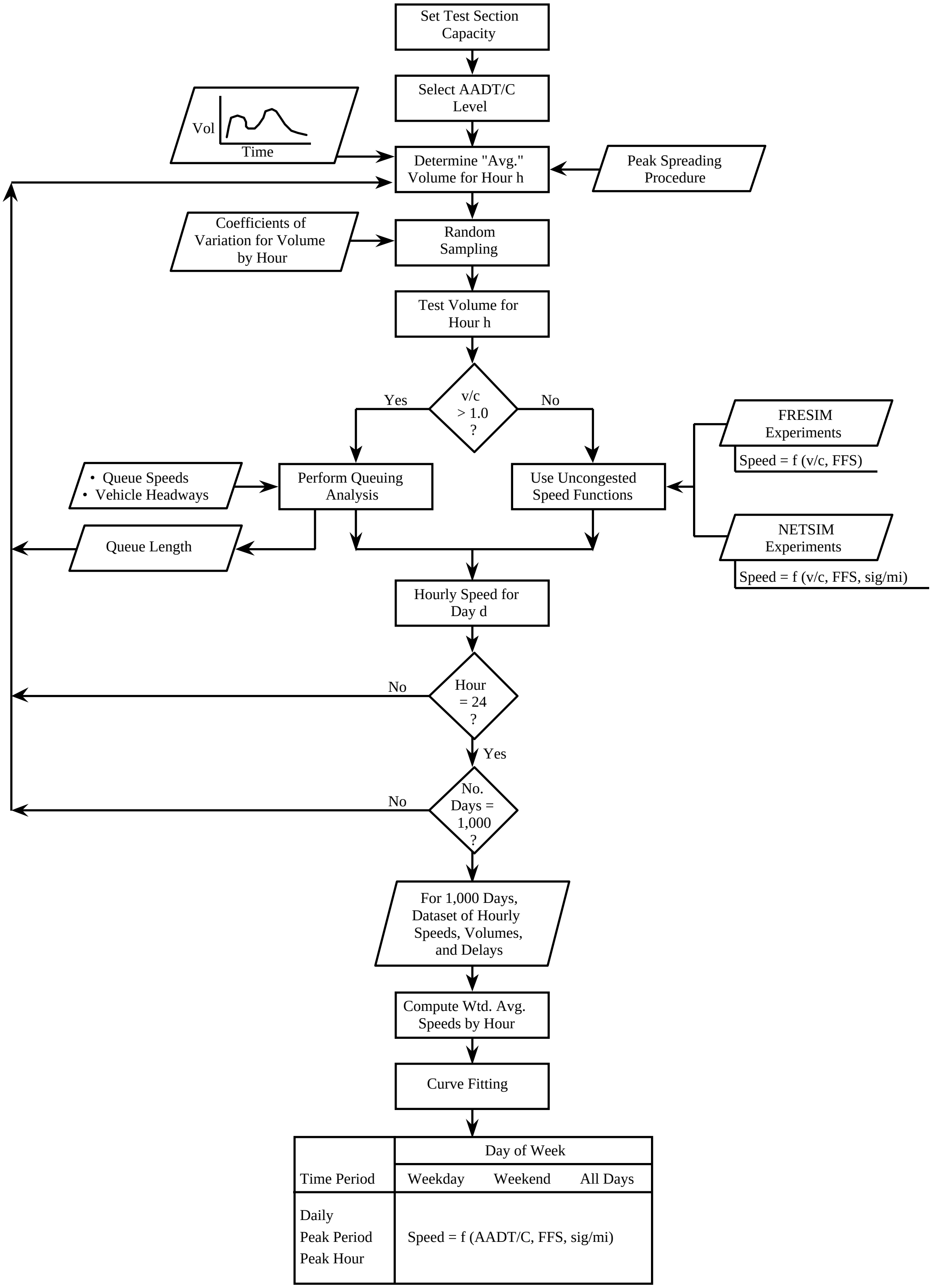
[7] Cambridge Systematics, Inc., *Sketch Methods for Estimating Incident-Related Impacts,* December 1998.

[8] Margiotta, Richard, and Cohen, Harry, *Roadway Usage Patterns: Urban Case Studies,* prepared for FHWA and VNTSC, July 22 ,1994.

Figure 2.2 Methodology for Delay Equations



Source: Cambridge Systematics, Inc., Sketch Methods for Estimating Incident-Related Impacts, December 1998.

So, the concepts of highway capacity are used as a starting point, the resulting delay estimates are higher using this method than if HCM-based methods are used. Because the equations consider queuing, and HCM methods do not, these equations will predict more delay than HCM methods. Note that the HCM recommends that queuing procedures be used for oversaturated conditions, but does not provide a specific method. For example, in Chapter 25 ("Ramp and Ramp Junction"), it simply states that LOS F exists "when demand exceeds capacity". There are no explicit delay calculations for the various degrees of LOS F.

Most of the interchanges studied are of very high design standards with no weaving areas, but there are a few (see Appendix A for interchanges have weaving areas). These weaves were ignored, and analysis focused on the merge junctures as the capacity control for a particular turning movement. Also, note that even though the HCM procedure is complex and requires unavailable data, it still measures delay crudely as one of the LOS categories. This paper recommends efforts should be made to consider weaving areas in the future. This is especially important for future analysis that may move away from the major commuter bottlenecks and include poorly designed interchanges with weaves.

However, to date field data have been lacking to validate this procedure. Also, there is some indication that the traffic variability component is too large for congested highways – day-to-day variability is smaller on congested highways. (The traffic distributions on which the procedure is based are now 15 years old). The HERS model uses this procedure and FHWA staff are aware of the need to re-think the traffic distributions and to perform at least limited field testing of the procedure.

A comparison of the capabilities of the method used in this study and the Ohio study appear in Table 2.2. Also, the delay results for two bottlenecks common to both studies appear in Table 2.2. The overall delay calculations are close, but the current method estimates slightly higher delay at both interchanges. The truck delays are noticeably different, due to the different sources of truck volume information. In the current study, percentages from FAF are used (from the previous FHWA freight bottleneck study) whereas in the Ohio study, actual counts of trucks (by the FHWA 13-class scheme) were used.

Application to the Current Study

The equations relate the AADT-to-capacity ratio to delay. Directional AADTs were obtained as described above. One-way capacities were calculated using a base capacity of 2,400 pcphpl, adjusted downward for the percentage of trucks at each merge juncture. If there is a lane-drop either at the merge juncture or a 1000 feet downstream, that is included in the analysis; these lane-drops are considered part of the interchange. Other lane-drops (such as those at bridges) are not interchange-related and have been identified in the previous FHWA freight bottleneck study as "general capacity-related bottlenecks".

The equations for estimating total daily delay for each direction were applied to each merge juncture, then, the higher delay was chosen. The travel time without queuing factors (H_u) is small in comparison to those for queuing (H_r). Total delay for each merge juncture is then:

$$\text{Total Delay at Merge Juncture} = (H_u * \text{VMT}) + (H_r * \text{AADT})$$

Table 2.2 Comparison of Methodologies and Delay Estimation

Technical Aspect	**Current Methodology**	**Ohio Methodology**
Analysis of individual merge areas	Yes	Yes
Ramp volumes	Derived synthetically from inflow / outflow volumes	Measured directly
Truck volumes	FAF percentages	Measured directly
Delay estimation	Uses HERS equations	Applies queuing procedure directly at each ramp juncture
Total Annual Delay (hrs)		
SR-315 at I-70 in Columbus	3,062,600	2,938,500
I-75 at I-74 in Cincinnati	2,589,200	1,923,00
Total Truck Delay (hrs)		
SR-315 at I-70 in Columbus	367,500	254,000
I-75 at I-74 in Cincinnati	305,800	166,250

VMT is calculated by multiplying AADT by ½ mile, assuming this is the distance traveled by vehicles as they pass through the interchange. Truck delay is obtained by multiplying total delay by percent trucks. This is clearly a simplifying assumption since it is assumed that the temporal distribution of trucks (hourly volumes) follow the same pattern as for total traffic.

Note that for this study, only ramp junctures were considered. An assessment of the interchanges at hand revealed that there were only two interchanges with weaving areas, mainly because these interchanges were designed to high standards.[9] The two interchanges are:

- I-77 @I-277 in Charlotte, NC (weave on I-77 NB)
- I-20 @I-285 in Atlanta, GA (weave on I-20 WB)

In some cases, interchanges are constructed so that two ramps handling turning movements merge, then the combined ramp merges with through traffic on the mainline. In such cases, the higher delay (rather than the sum was chosen) because when two bottlenecks are closely spaced, one will control the operation. Therefore, only one delay value for each exiting direction is used. Figure 2.2 shows the equations for estimating the delay factors. Total delay for the interchange is then summed over all exiting directions for the interchange.

Figure 2.3 shows an example of what the analysis reveals at an individual interchange. Note that only two merge junctures create delay problems.[10] These results are very typical – not all ramps

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[9] The satellite photos were used to determine if weaves existed. From these, it can be easily determined if ramps are "directional" (as defined by the AASHTO Design Guide) or shared (e.g., "loops in adjacent quadrants).

and turning problems are bottlenecks at an interchange. Appendix B shows the delay results for each of the exiting directions at the interchanges.

Limitations of the Methodology

The goal of this project was to see if a cost-effective methodology could be developed for analyzing bottlenecks that is based on the specific physical restrictions of complex types of bottlenecks (interchanges). Generally, as analytic procedures become more detailed, their replication of reality will increase in accuracy and fewer assumptions have to be made, but the data requirements and operation become more onerous. For bottleneck analysis, the methods range from:

- the very abstract approach used in the AHUA and previous FHWA bottleneck studies (using the highest value for AADT/C for the intersecting highways, based on HPMS data), to
- microsimulation of the entire interchange using actual hourly (or sub-hourly) traffic volumes.

The methodology used here falls between these two ends of the spectrum, closer to the AHUA methodology because it is still a "planning level" analysis (in HCM terms). The major limitations of the methodology are as follows.

- Turning movements (total daily volume) on the ramps of the interchanges are derived synthetically rather than using actual (measured) turning volumes. While the method used to derive turning movements has been in standard planning practice for a long time, there is still error associated with it.
- Truck volumes on the interchange ramps are computed using global percentages from HPMS (to adjust capacity) and from FAF (to get "freight truck" delay").
- Hourly distributions of traffic are assumed to be the same as those that were to develop the HERS delay equations. Hourly truck distributions are assumed to follow the same temporal pattern as total traffic.
- The internal workings of the HERS delay equations are currently being reviewed and updated. The assumptions used in the development of the present equations are now 15 years old and need to be re-visited.

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[10] Note: This figure is from the *Ohio Freight Mobility* report, but the same two ramps are identified as bottlenecks in both studies.

Figure 2.2 Delay Equations From Reference (4) Used in the Study

A.M. Peak Direction, 24-hour Delay

Travel Time without Queuing (hours per vehicle mile)

$$H_u = 1 / \text{Speed} = (1 / S_f)(1 + 5.44\text{E-}12 * X^{10})$$

for X <= 8

$$H_u = 1 / \text{Speed} = (1 / S_f)(1.23\text{E+}00 - 7.12\text{E-}02 * X + 6.78\text{E-}03 * X^2 - 1.83\text{E-}04 * X^3)$$

for X > 8

Delay Due to Recurring Queues (hours per vehicle using the bottleneck)

$$H_r = \text{RECURRING DELAY} = 0$$

for X <=8

$$H_r = \text{RECURRING DELAY} = 6.77\text{E-}03 * (X - 8) - 4.13\text{E-}03 * (X - 8)^2 + 1.29\text{E-}03 * (X - 8)^3$$

for X > 8

P.M. Peak Direction, 24-hour Delay

Travel Time without Queuing (hours per vehicle mile)

$$H_u = 1 / \text{Speed} = (1 / S_f)(1 + 7.37\text{E-}12 * X^{10})$$

for X <= 8

$$H_u = 1 / \text{Speed} = (1 / S_f)(1.13\text{E+}00 - 4.39\text{E-}02 * X + 4.68\text{E-}03 * X^2\ 1.32\text{E-}04 * X^3)$$

for X > 8

Delay Due to Recurring Queues (hours per vehicle using the bottleneck)

$$H_r = \text{RECURRING DELAY} = 0$$

for X <=8

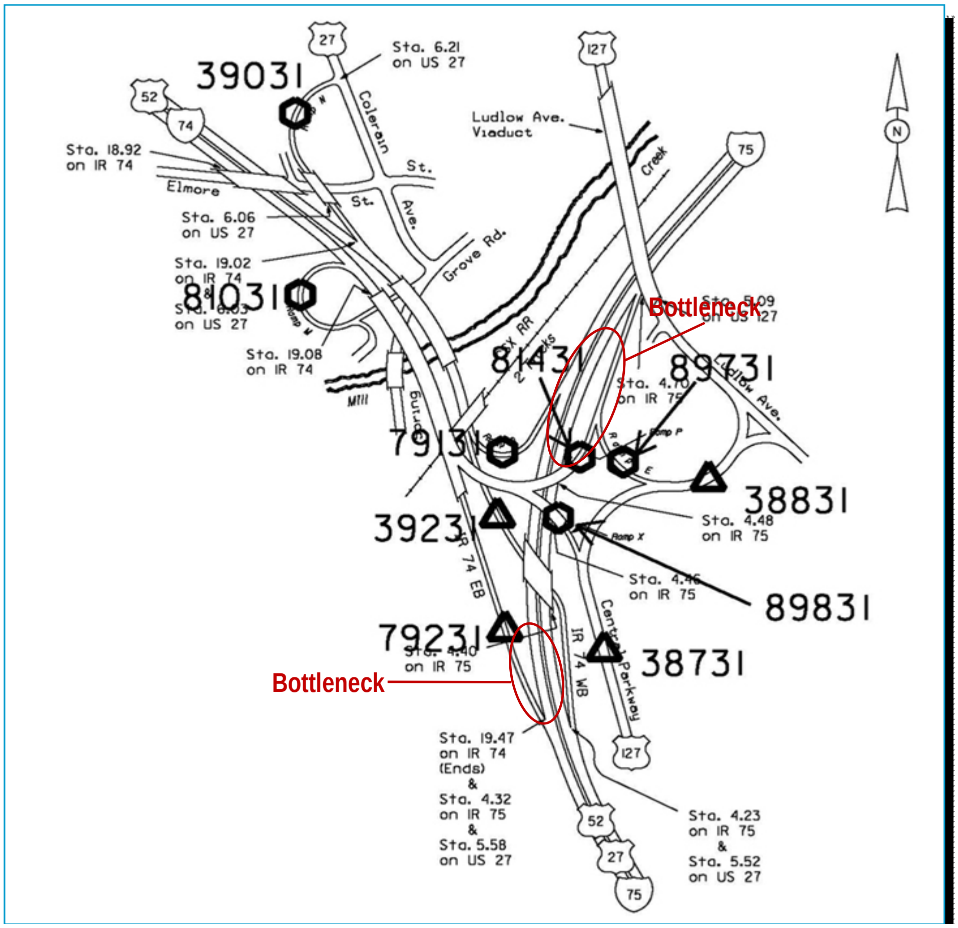
$$H_r = \text{RECURRING DELAY} = 4.11\text{E-}03 * (X - 8) + 1.26\text{E-}03 * (X - 8)^2 + 4.03\text{E-}04 * (X - 8)^3$$

for X > 8

where: S_f = free flow speed = 60 mph

$X = AADT / C$

Figure 2.3. Merge Junctures That Are Bottlenecks, I-74/I-75 Interchange, Cincinnati, OH



3. RESULTS AND RECOMMENDATIONS

3.1 Study Results

The bottleneck delay results from this study are compared to those from Reference (1) in Table 3.1. The bottlenecks are listed in order from the highest to the lowest based on the current delay estimates.

- The rankings clearly have shifted as a result of applying the new methodology, but a major finding of the previous FHWA Freight Bottleneck study – that truck bottlenecks (in terms of total delay) occur at urban commuter bottlenecks – is intact. (The total truck delay at these locations is still much higher than other forms of bottlenecks identified in the previous study, e.g., steep grades). Because only the top 23 bottlenecks from the previous study were considered here, the rankings shown here are by no means comprehensive – it's possible that additional bottlenecks, if analyzed in a similar manner, could replace some on the current list of 23.
- The total delay estimates for the worst bottlenecks are in close agreement, indicating that the AHUA methodology is a good screening tool, but misses capturing the nuances of individual interchange operation.
- Proceeding down the list, there is a much sharper drop-off in delay. The reason for this is that in the original methodology, a single AADT/C value was used for the entire interchange. This value is based on HPMS data and the value tended to be very similar for the high-delay interchanges. In the current methodology, there is much more distinction between both the AADT/C values for the individual merge junctures and the volumes of trucks using them.
- Chicago and Los Angeles both have five of the top truck bottlenecks, followed by three in Atlanta. This is roughly commensurate with the number of commuter bottlenecks found in the AHUA study but Chicago's status is elevated when trucks are considered.
- It was originally thought that once traffic volumes were developed and the basic type of interchange was established (e.g., cloverleaf, full directional), that relationships between delay and general interchange type could be developed. However, this proved to be unfruitful. Part of the problem is that there are almost an infinite number of variations on the basic interchange types. Specifically, the interchanges analyzed in this report are complex and defy categorization. More problematic is that the fact the traffic flow is strictly a function of the geometric details. The specifics of the merge junctures (number of lanes entering and exiting) were found to determine the delay and this information cannot be gleaned from the general interchange typology.

Table 3.1 Annual Delay at Major Truck Bottlenecks

	Annual Delay (hrs)		
	Current Study		Previous FHWA Freight Bottleneck Study
Bottleneck Name	**Total**	**Truck**	**Truck**
I-405 at I-605 in Los Angeles, CA	19,363,000	2,662,600	1,245,500
SR-60 at I-605 in Los Angeles, CA	17,004,600	2,400,200	1,314,600
I-75 at I-285 in Atlanta, GA	17,330,400	2,253,000	1,497,300
I-55 at Pulaski in Chicago, IL	12,590,600	1,888,600	1,300,400
I-80 @ I-580/I-880 Oakland, CA	17,192,800	1,838,700	1,196,700
I-285 at I-85 in Atlanta, GA	13,962,100	1,815,100	1,641,200
I-90/94 at I-290 in Chicago, IL	22,427,800	1,600,300	1,544,900
I-80 at I-94 split in Chicago, IL	7,585,300	1,365,300	1,343,600
I-15 at I-10 in Los Angeles, CA	7,248,200	1,308,300	1,522,800
I-880 at SR-238 in Oakland, CA	11,951,400	1,200,300	1,106,700
I-90 at I-290 in Buffalo, NY	6,563,400	816,300	1,661,900
I-93 at I-95 in Boston (South), MA	5,189,400	726,500	1,280,100
I-77 @I-277 in Charlotte, NC (South)	3,884,200	660,300	1,487,100
I-90 at I-94 split in Chicago, IL	4,871,100	584,500	1,512,900
I-17 at I-10 in Phoenix, AZ	4,153,500	493,200	1,608,500
I-710 at I-105 in Los Angeles, CA	4,779,800	425,200	1,380,300
SR-315 at I-70 in Columbus, OH	3,062,600	367,500	1.097,600
I-75 at I-74 in Cincinnati, OH	2,589,200	305,800	1,128,900
I-20 at I-285 in Atlanta, GA	2,289,200	285,100	1,359,400
I-75 at I-85 in Atlanta, GA	3,894,600	272,600	1,288,800
SR-134 at SR-2 in Los Angeles, CA	3,997,500	267,600	1,489,400
I-290 at I-355 in Chicago, IL	3,295,200	263,600	1,246,500
I-93 at I-90 in Boston, MA	2,411,300	175,800	1,041,800

3.2 Recommendations for Future Bottleneck Monitoring (Freight and Non-freight)

- The study demonstrates that the basic information to monitor the performance of bottlenecks – interchange configuration/geometrics and traffic – can be cost-effectively obtained from existing sources. However, a few improvements in the process are recommended. More refined traffic data may be obtained directly from state DOTs. This would include primarily directional AADTs on each of the approaches of the interchanges. If temporal traffic distributions could be obtained, then instead of applying the default delay equations (which are based on fixed temporal distributions) the queuing procedures used in the Ohio study could be applied directly to each merge juncture. Finally, data on the temporal distributions of trucks – ideally site-specific – would improve the estimates of truck delay.
- Additional types of traffic flow restrictions at interchanges should be considered. This study assumed that the "chokepoints" of the intersection are where two or more freeway ramps merge with each other or the mainline. Given the nature of the interchanges

studied, nearly all of which are fully directional or mostly so, this assumption was adequate for our purposes. However, if the method is to be applied more universally, other types of restrictions need to be added, such as:

  - Weaving areas
  - Restricted diverge areas
  - Limited acceleration lanes
  - Other types of limited geometry (short radius loops).

  For all of these, the way the method will assess them is through the estimate of capacity (to determine if queuing is occurring).

- Work should continue on FHWA's Office of Operations Bottleneck Initiative. This initiative gathered subjective information from FHWA's Division offices on the worst bottlenecks in each state. Basic interchange configuration and geometrics should be added to the Office of Operations database for a subset of interchanges (e.g., major freeway-to-freeway interchanges). HPMS–based AADTs for interchange approach segments can also be added for this subset.
- The AHUA methodology should only be used as a screening tool. It has proven to be an effective first cut at bottleneck delay estimation and ranking, but as this study has shown, interchanges are too unique in geometrics and traffic patterns for that method to produce operations-level rankings.
- The information developed here should be considered in routine HPMS data collection. To reiterate, data on ramp juncture configuration should be complied for each "exit" of the interchange (an "exit" is where traffic is moving away from the interchange). The data structure must allow for multiple ramp junctures at each "exit". (Two ramps from flyovers may merge prior to the combined ramp merging with the mainline.) The data should include:
  - Number of lanes on each approach to the merge juncture
  - Number of lanes immediately downstream of the merge juncture
  - Number of lanes 1,500 feet downstream of the merge juncture.
- In addition to the ramp juncture data used in this study, additional data on interchanges will prove useful in future policy analyses. While only a few key pieces of data were obtained for this study from the satellite photos (interchange configuration, and number of lanes and merge junctures), additional data may be gleaned from the photos including:
  - Turning radii
  - Weaving areas
    - HCM weave type
    - Weaving area length
  - Other points of restrictive highway geometry
  - Number of structures

  - Collector / distributor and auxiliary lanes

  This information could be valuable in future policy work and could be gathered without intruding upon state HPMS data collectors. A key task is to be able to map the interchanges to HPMS's location referencing system, but this study has shown that it is possible to identify the approach segments to the interchanges by using the existing LRS data and observing volume changes on successive segments. To make the job manageable, only freeway-to-freeway interchanges and those additional interchanges identified as bottlenecks in the Office of Operations work could be coded initially, with additional interchanges added in future years.

- The analytic procedures developed here should be considered for inclusion within the HERS model. Specifically, *interchange deficiency analysis* should be added to HERS as a companion to its current general capacity deficiency analysis (i.e., number of lanes on mainline, noninterchange-influenced segments). The interchange deficiency analysis would be based on the methodology used here. This inclusion will be particularly valuable when HERS migrates to a network-based (rather than sample section-based) framework. Since it is clear that interchanges and there immediate influence areas are the physical items that control congestion on urban freeways, performing delay analysis based on them will provide a much more realistic assessment of capacity deficiencies and needs.

- The HERS delay equations are currently in review. The data on which the present equations were developed are now 15 years old. In particular, the assumptions about traffic variability need to be checked, particularly for congested highways. Some level of field validation would also be productive.

APPENDIX A

INTERCHANGE CONFIGURATIONS

Due to file size limitations the schematics of individual interchanges is posted as a separate document. Schematics, similar to Figure 2.1 for all the interchanges listed in Table 2.1 are available in the separate document or upon request at kwhite@dot.gov.

APPENDIX B

DELAY AT INTERCHANGE MERGE JUNCTURES

		Annual Delay (hrs)	
Bottleneck Name	**Interchange Exit**	**Total**	**Trucks**
I-15 at I-10 in Los Angeles	EB	4,471,900	894,400
	NB	642,200	70,600
	SB	927,900	102,100
	WB	1,206,300	241,300
I-17 at I-10 in Phoenix	EB	908,400	118,100
	NB	374,700	41,200
	SB	1,962,100	215,800
	WB	908,400	118,100
I-20 at I-285 in Atlanta	EB	515,100	72,100
	NB	433,200	43,300
	SB	451,000	45,100
	WB	889,900	124,600
I-285 at I-85 in Atlanta	EB	2,939,800	382,200
	NB	4,537,900	589,900
	SB	2,522,900	328,000
	WB	3,961,400	515,000
I-290 at I-355 in Chicago	EB	444,600	35,600
	NB	319,400	25,500
	SB	2,531,200	202,500
I-405 at I-605 in Los Angeles	EB	878,500	131,800
	NB	12,875,700	1,931,400
	SB	13,500	2,000
	WB	5,595,200	597,500
I-55 at Pulaski in Chicago	EB	6,279,300	941,900
	NB	16,000	2,400
	SB	16,000	2,400
	WB	6,279,300	941,900
I-710 at I-105 in Los Angeles	EB	530,800	84,900
	NB	2,137,900	106,900
	SB	949,000	47,500
	WB	1,162,100	185,900
I-75 at I-285 in Atlanta	EB	1,031,500	134,100
	NB	6,221,100	808,700
	SB	4,117,700	535,300
	WB	5,960,100	774,800

Bottleneck Name	Interchange Exit	Annual Delay (hrs) Total	Trucks
I-75 at I-74 in Cincinnati	NB	1,575,300	189,000
	SB	766,500	92,000
	WB	247,400	24,700
I-75 at I-85 in Atlanta	NB	3,894,600	272,600
I-77 @I-277 in Charlotte, NC (South)	EB	140,400	23,900
	NB	349,800	59,500
	SB	3,311,400	562,900
	WB	82,600	14,000
I-80 @ I-580/I-880 Oakland, CA	EB	167,300	15,100
	NB	11,655,100	1,340,300
	WB	5,370,400	483,300
I-80 at I-94 split in Chicago	EB	2,545,900	458,300
	NB	157,000	28,300
	SB	4,321,400	777,900
	WB	561,000	101,000
I-880 at SR-238 in Oakland	EB	383,500	43,500
	NB	5,206,600	520,700
	SB	6,361,300	636,100
I-90 at I-290 in Buffalo	EB	2,745,800	274,600
	NB	1,142,600	274,200
	SB	2,675,000	267,500
I-90 at I-94 split in Chicago	NB	4,798,600	575,800
	SB	72,500	8,700
I-90/94 at I-290 in Chicago	EB	3,746,200	412,100
	NB	7,749,300	387,500
	SB	6,696,700	334,800
	WB	4,235,600	465,900
I-93 at I-90 in Boston	EB	528,300	42,300
	NB	899,100	62,900
	SB	814,500	57,000
	WB	169,600	13,600

Bottleneck Name	Interchange Exit	Annual Delay (hrs) Total	Trucks
I-93 at I-95 in Boston (South)	EB	1,106,600	154,900
	SB	2,721,800	381,100
	WB	1,360,900	190,500
SR-134 at SR-2 in Los Angeles	EB	1,750,500	52,500
	NB	1,326,100	159,100
	SB	315,300	37,800
	WB	605,600	18,200
SR-315 at I-70 in Columbus	EB	1,484,100	178,100
	NB	133,200	16,000
	SB	1,102,800	132,300
	WB	342,500	41,100
SR-60 at I-605 in Los Angeles	EB	6,146,800	922,000
	NB	2,509,000	301,100
	SB	2,509,000	301,100
	WB	5,839,900	876,000

I-90 at I-290 Interchange
Buffalo, NY

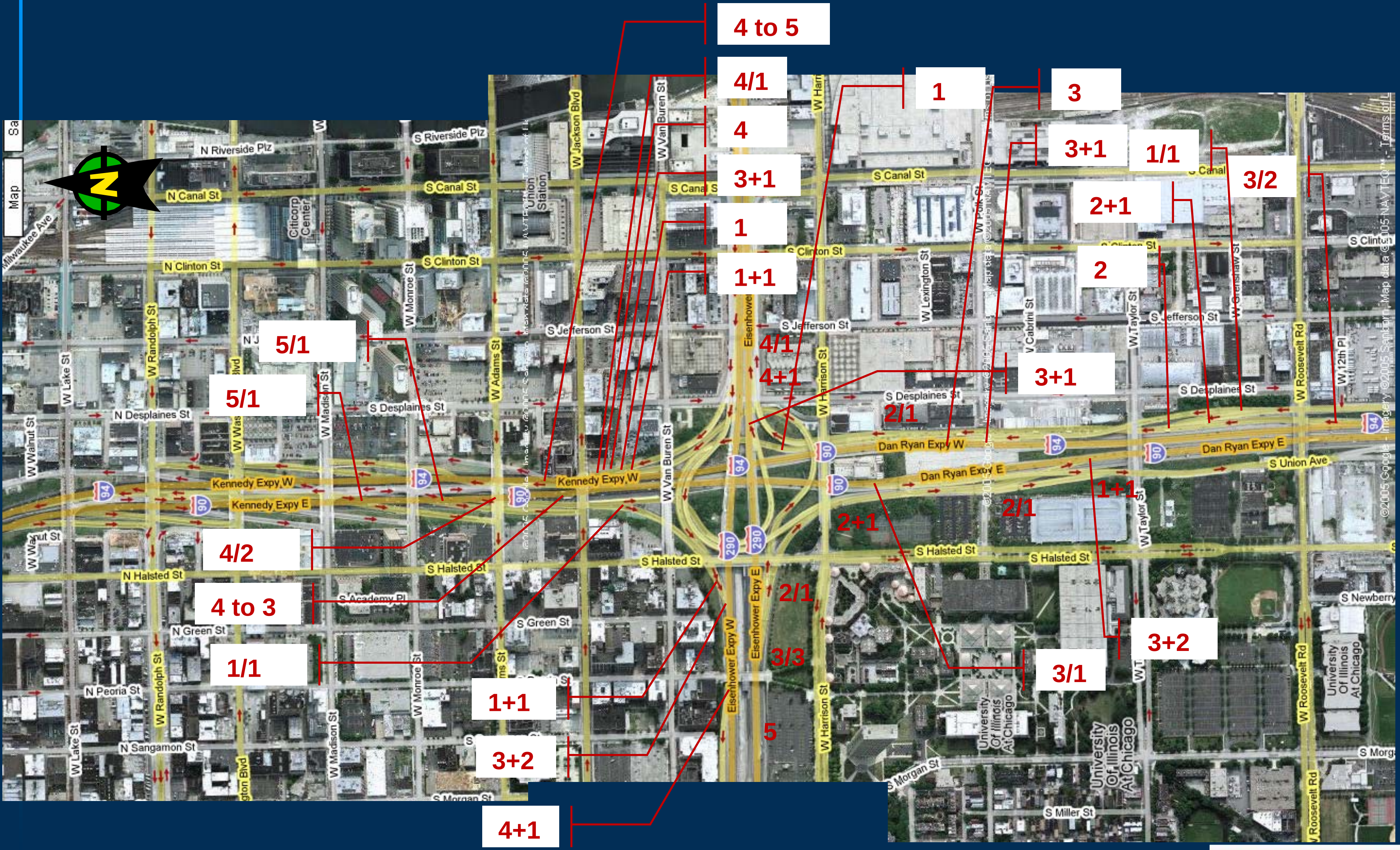
I-285 at I-85 Interchange
Northeast of Atlanta, GA

I-17 at I-10 Interchange

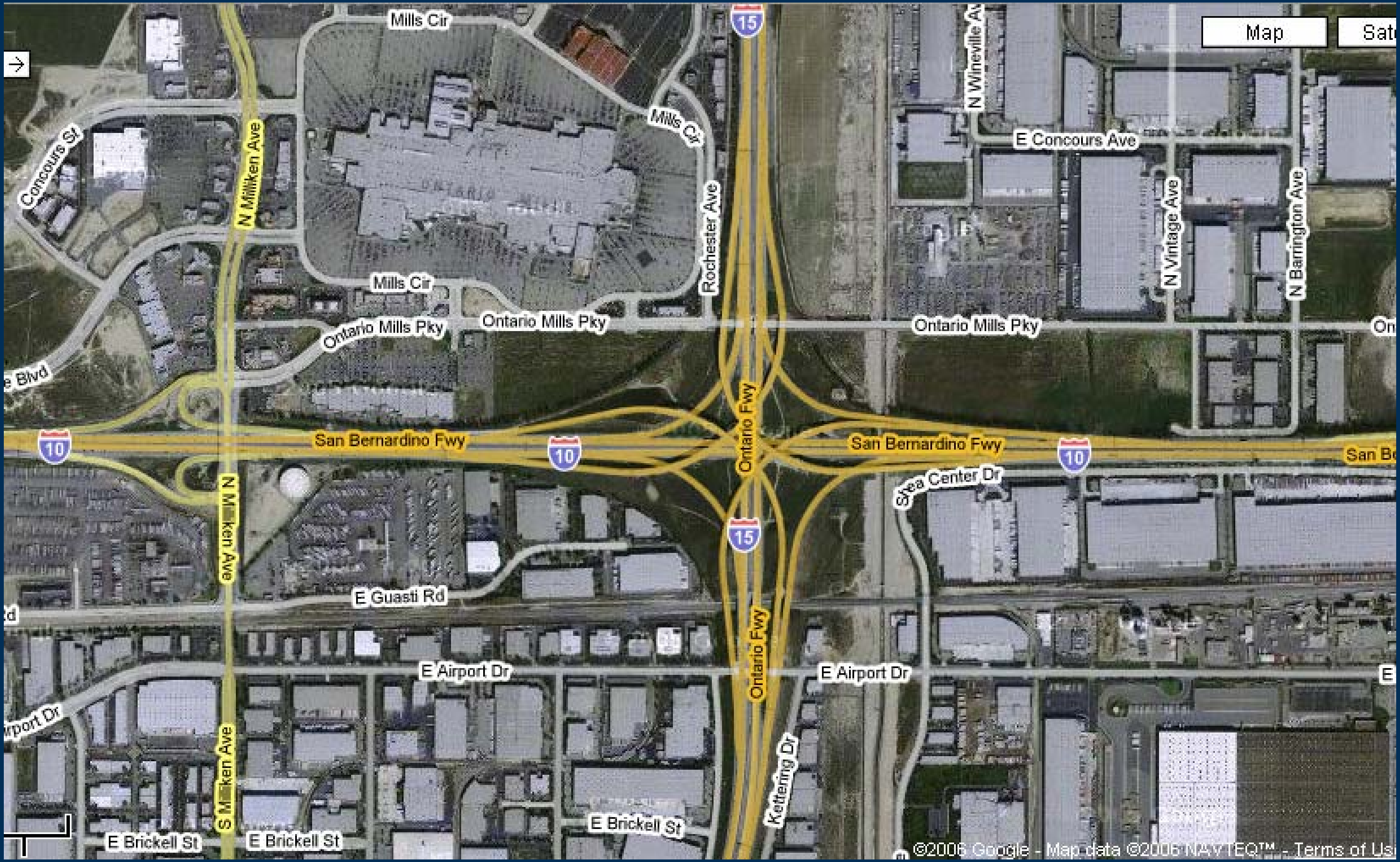
Phoenix, AZ

I-90/94 at I-290 Interchange

Chicago, IL



I-10 at I-15 Interchange
Los Angeles, CA



I-94 and I-90 Split

Southeast of Chicago, IL

I-285 at I-75 Interchange

North of Atlanta, GA

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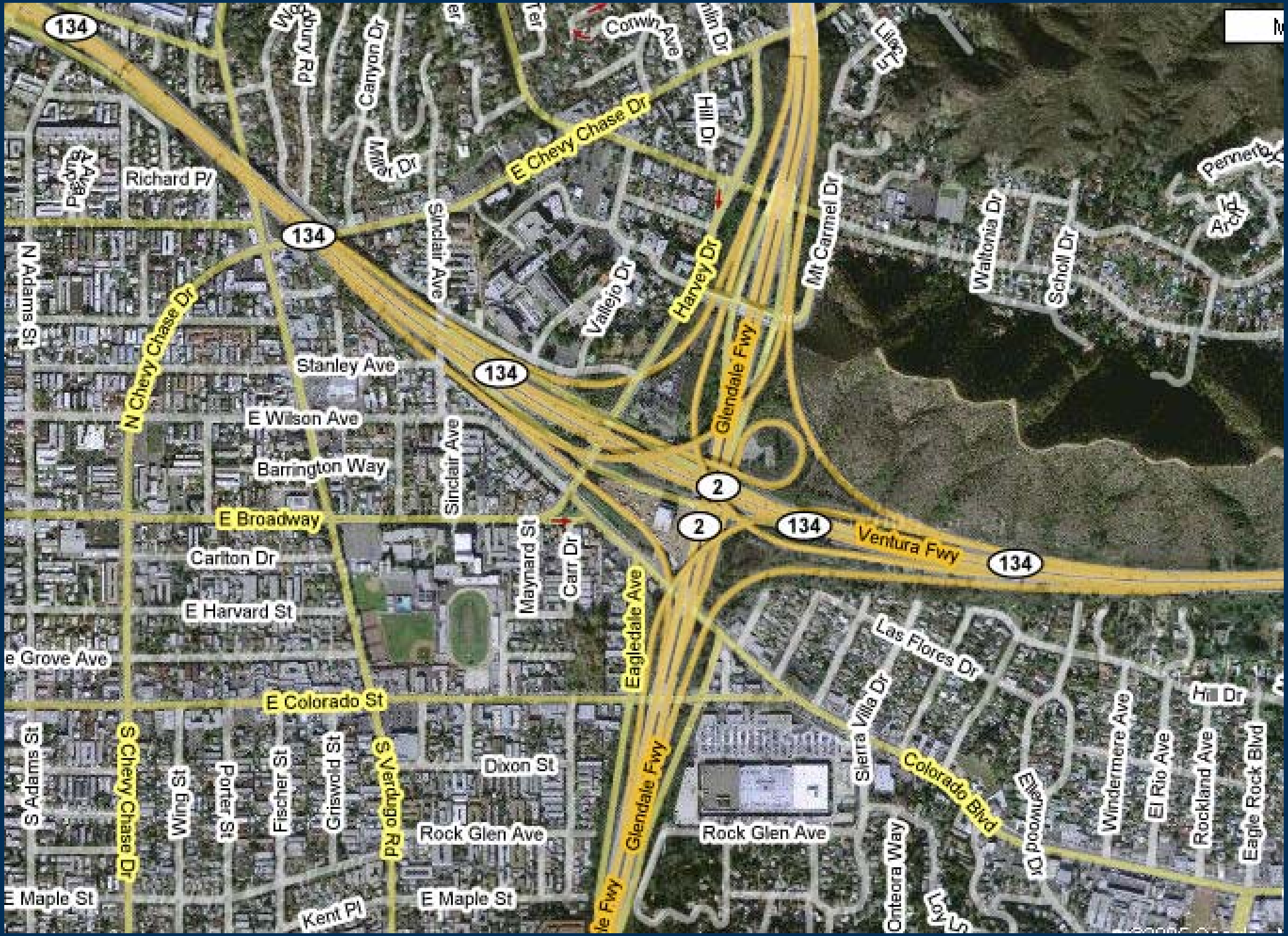
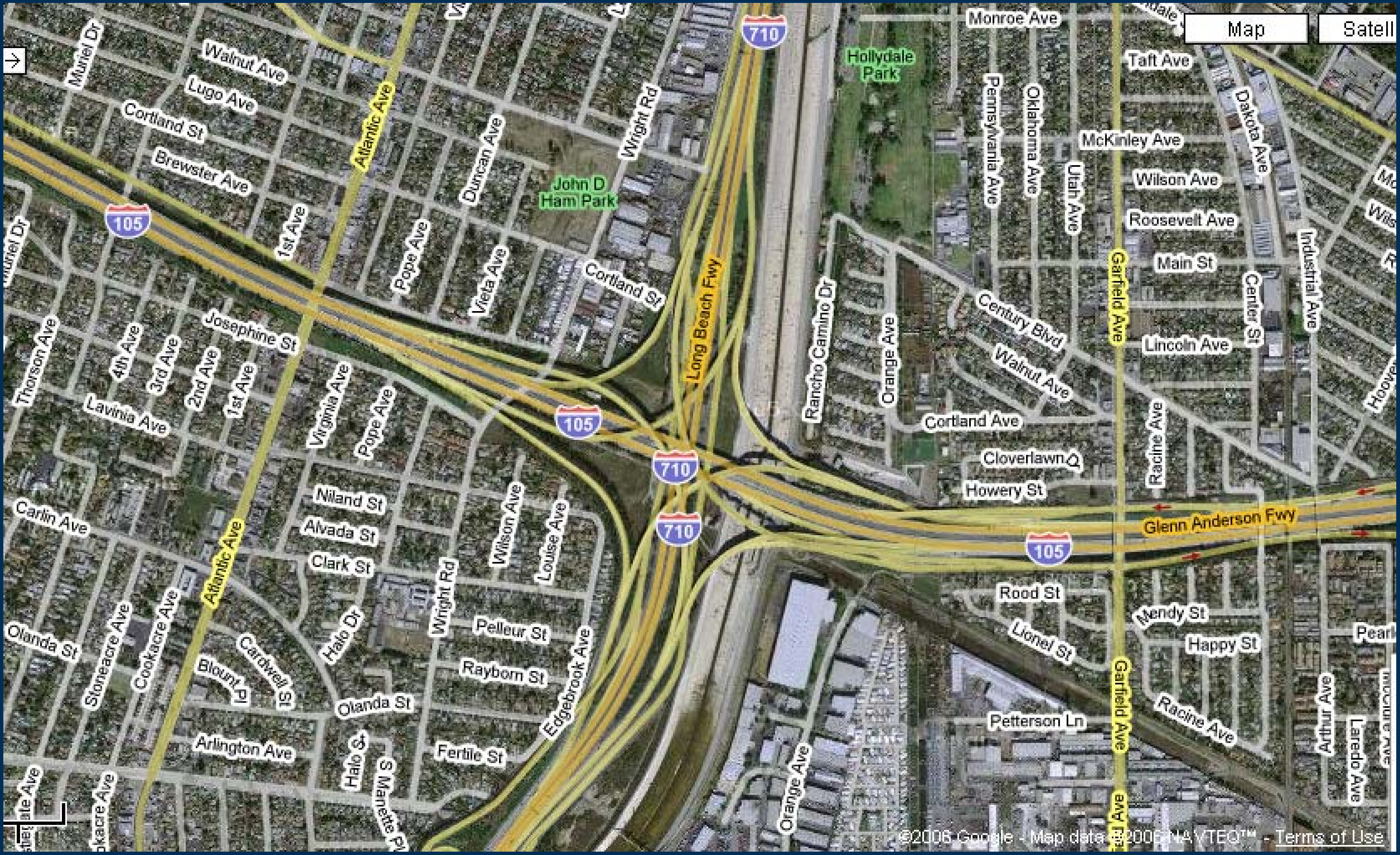
SR-134 at SR-2 Interchange
Los Angeles, CA



I-77 at I-277 Interchange
Charlotte, NC (South Interchange close-up)

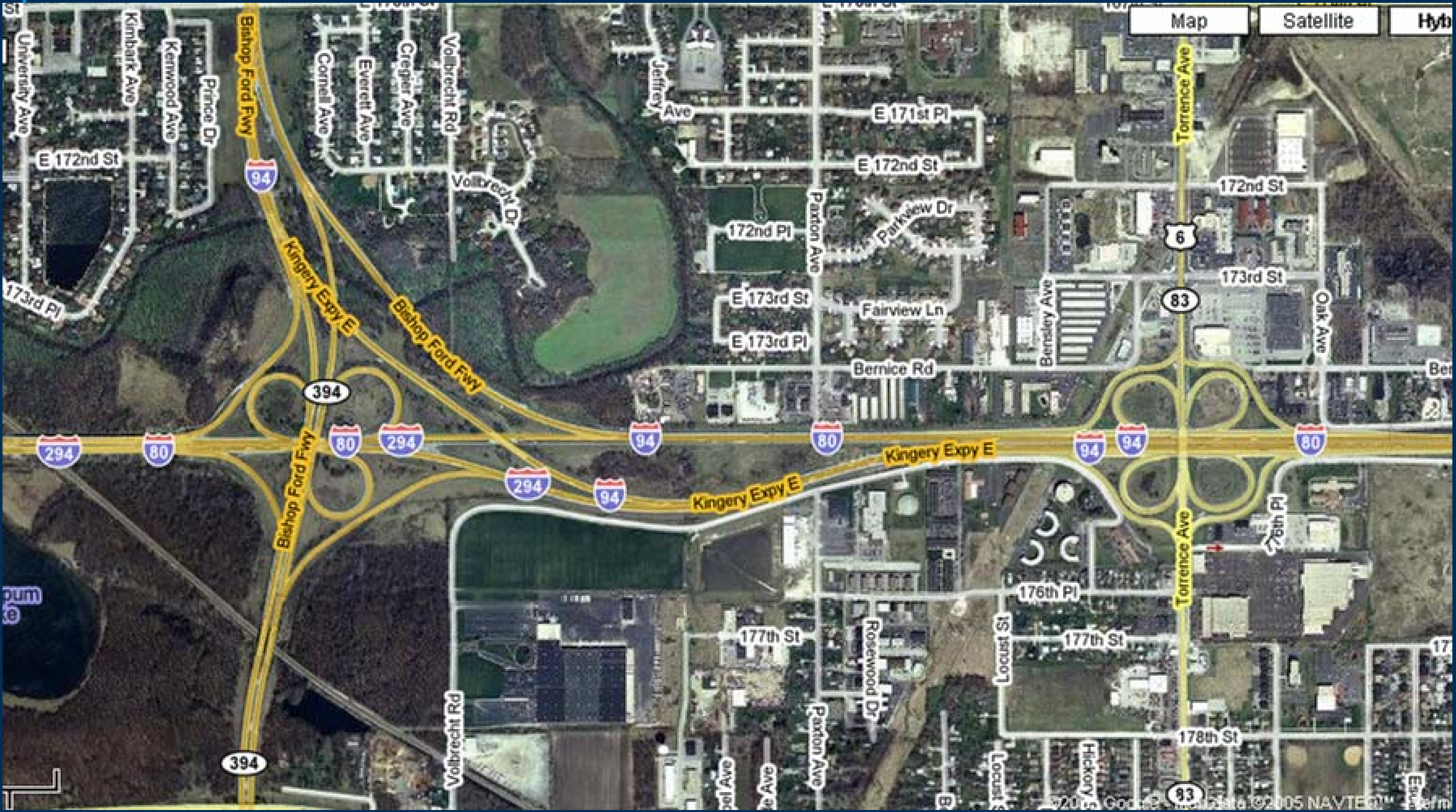
I-710 at I-105 Interchange
Los Angeles, CA



I-20 at I-285 Interchange
East of Atlanta, GA

I-80 and I-94 Split

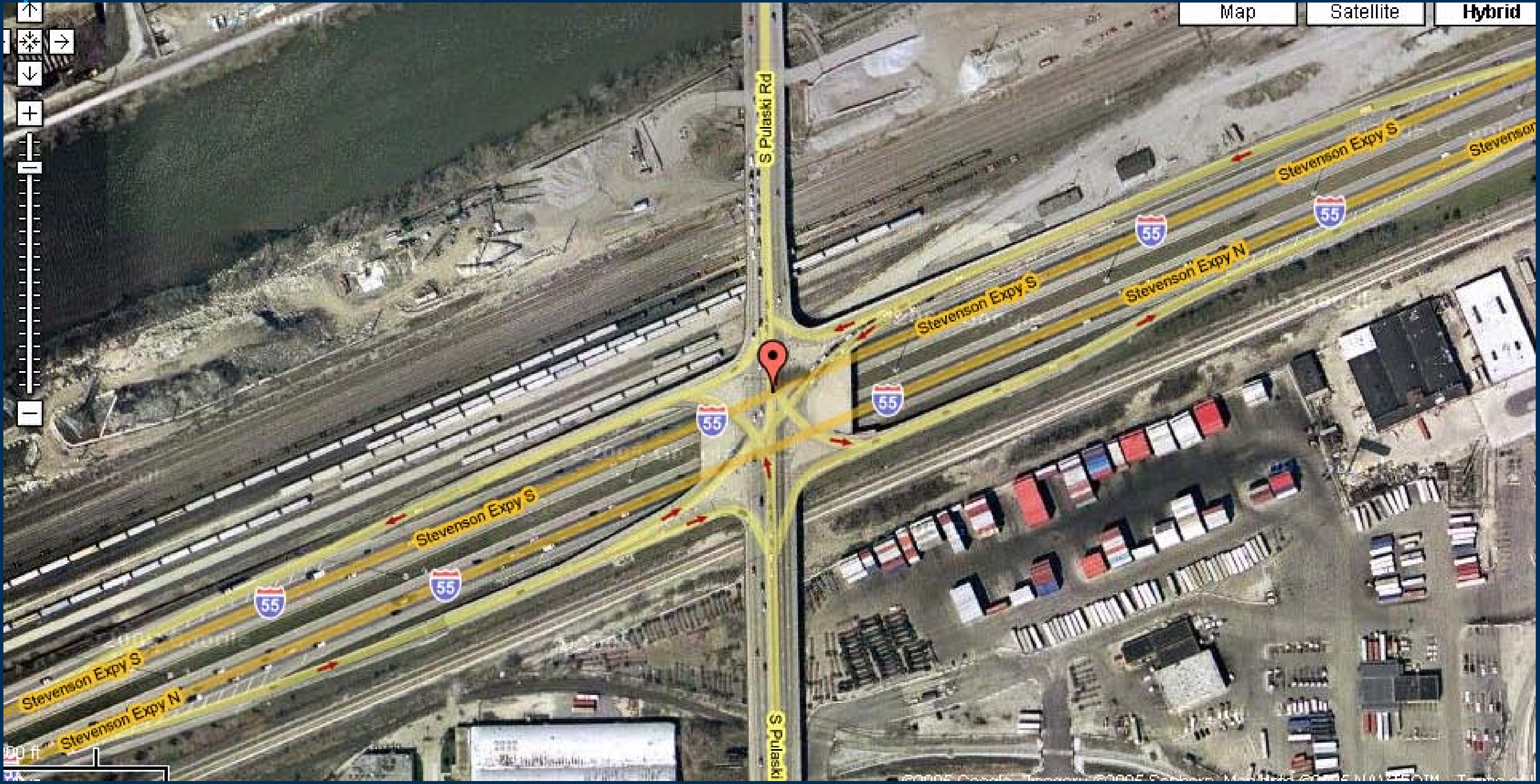
South of Chicago, IL



SR-60 at I-605 Interchange
Los Angeles, CA

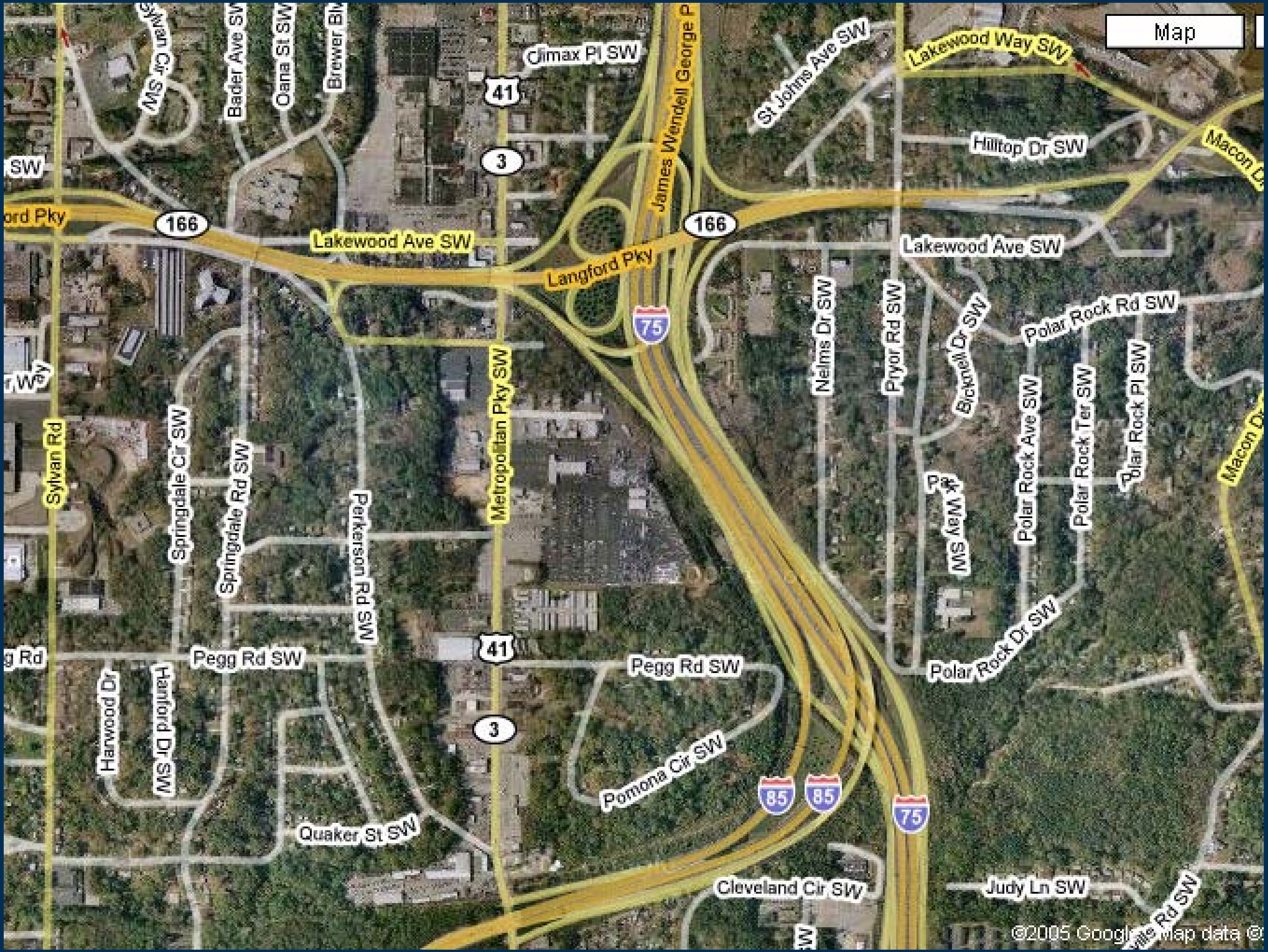
I-55 at Pulaski Rd Interchange

Chicago, IL



I-75 at I-85 Split

Atlanta, GA



I-93 at I-95 Interchange
South of Boston, MA

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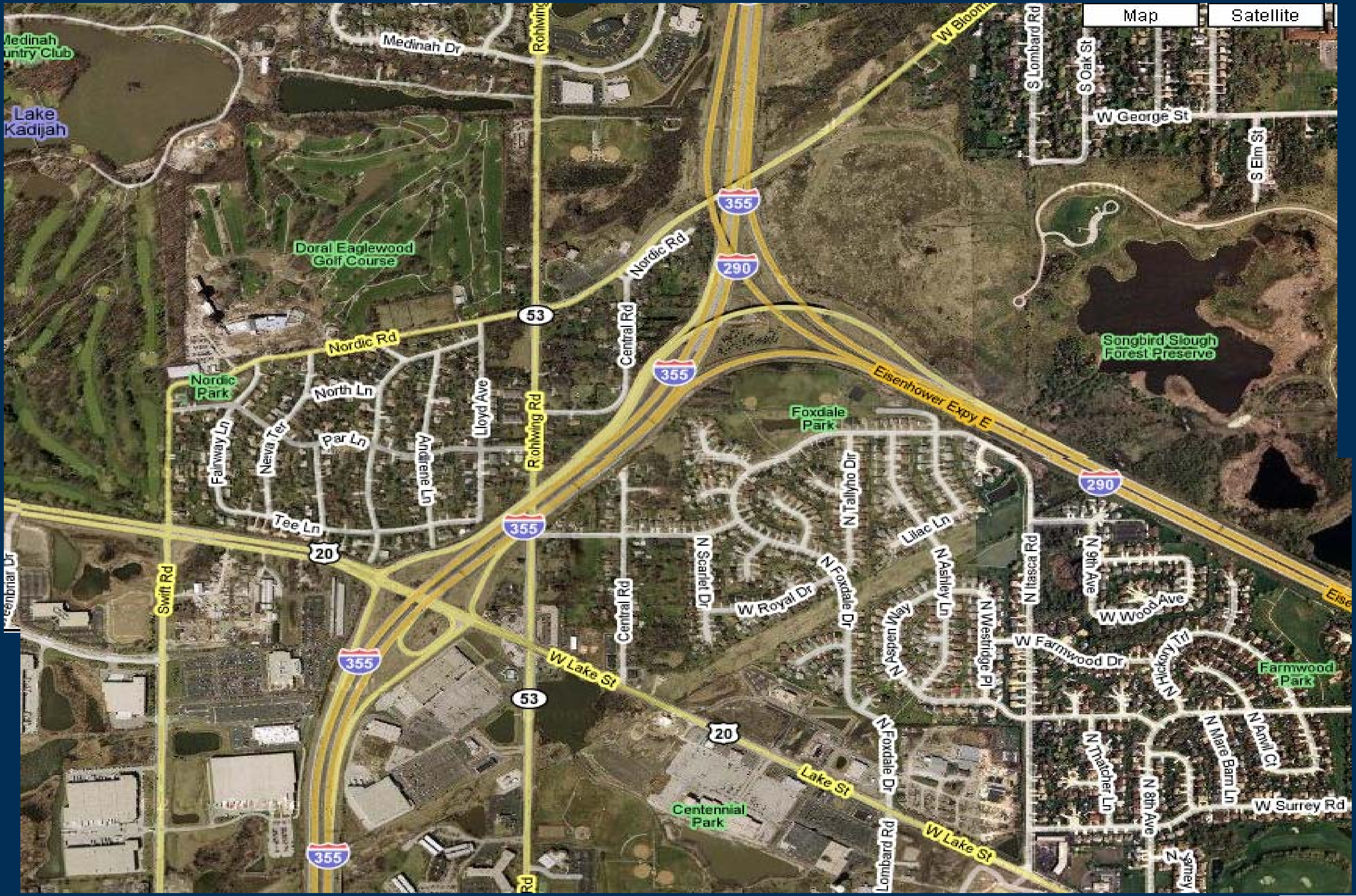
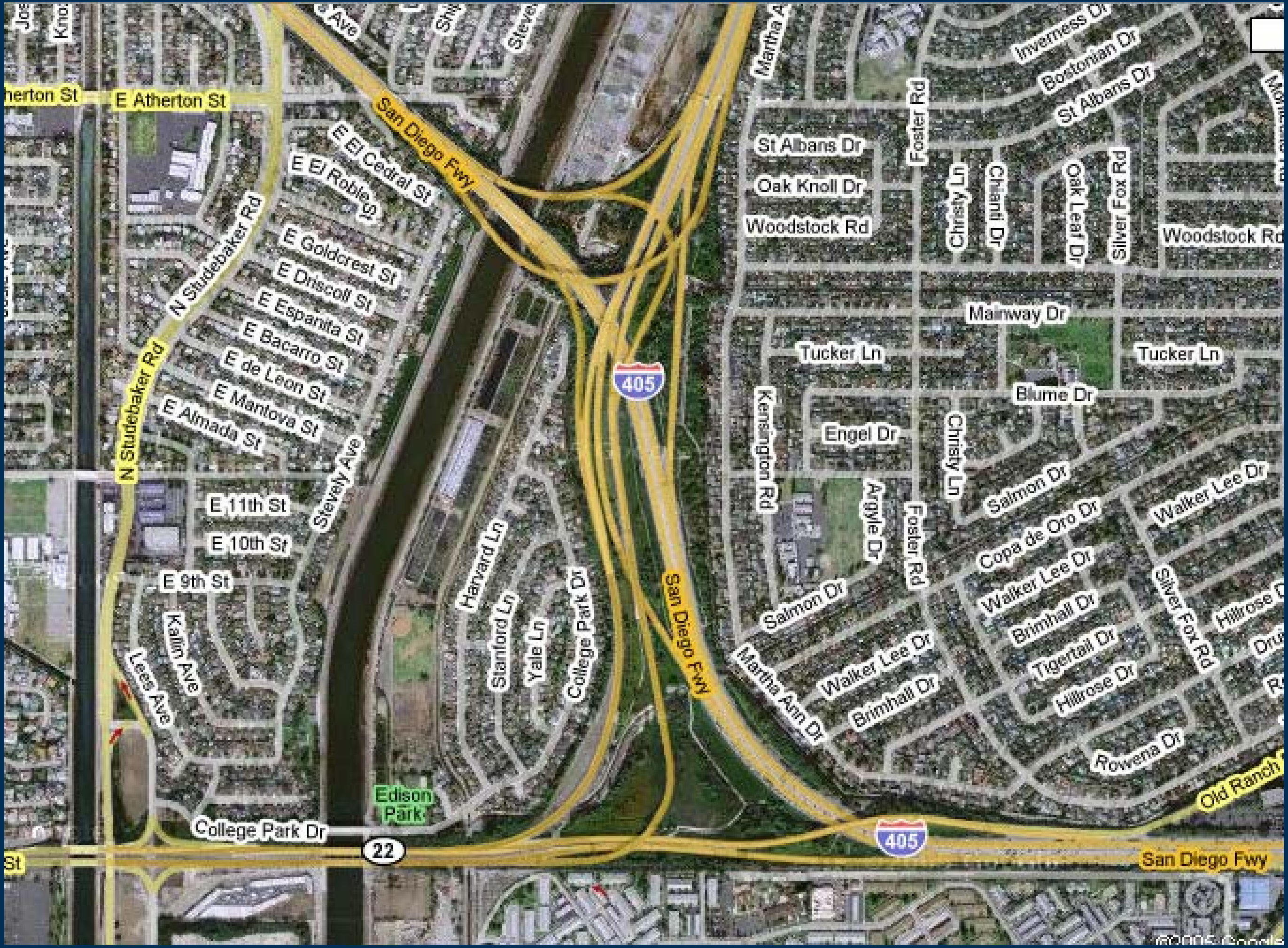
I-290 at I-355 Interchange

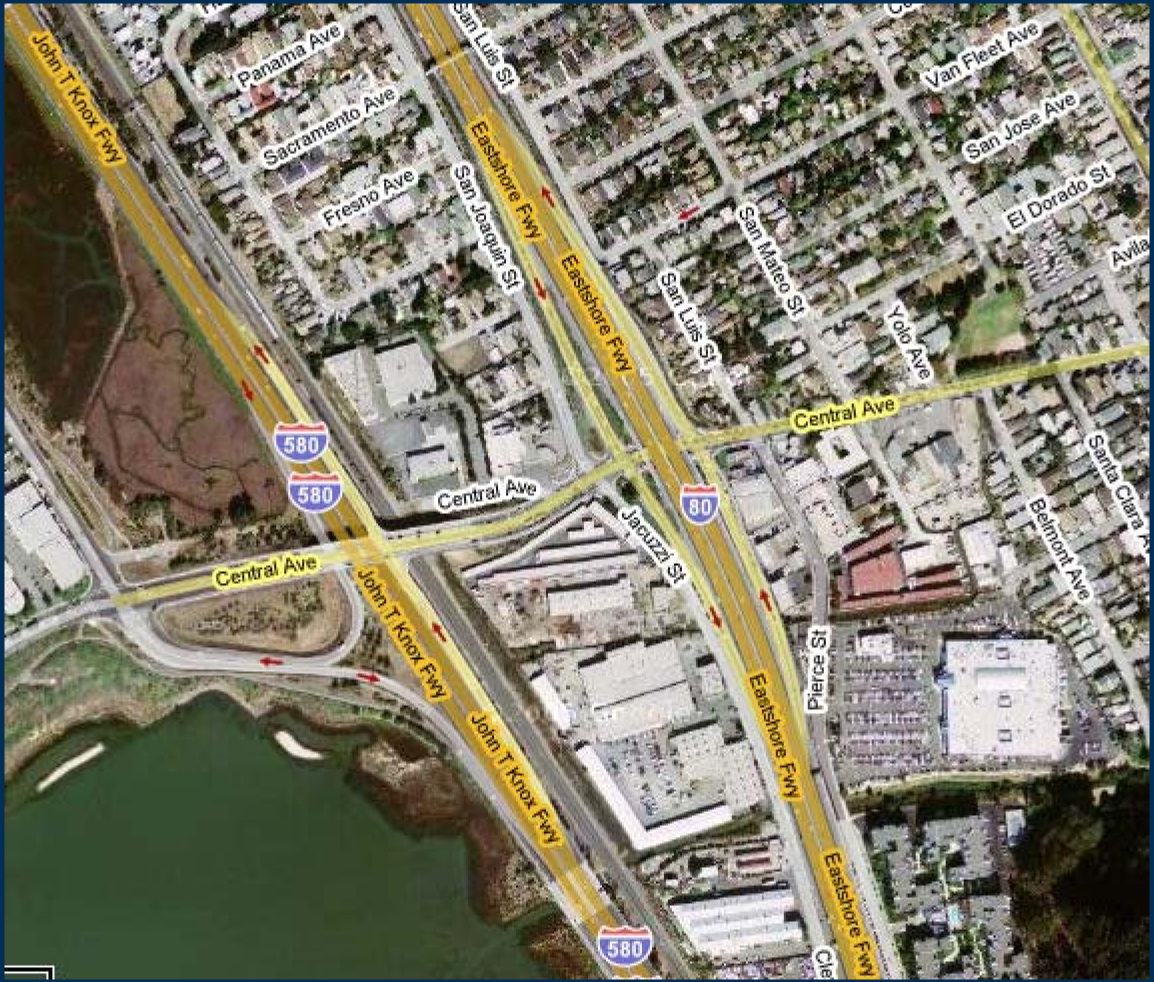
West of Chicago, IL



I-405 at I-605 Interchange
Los Angeles, CA

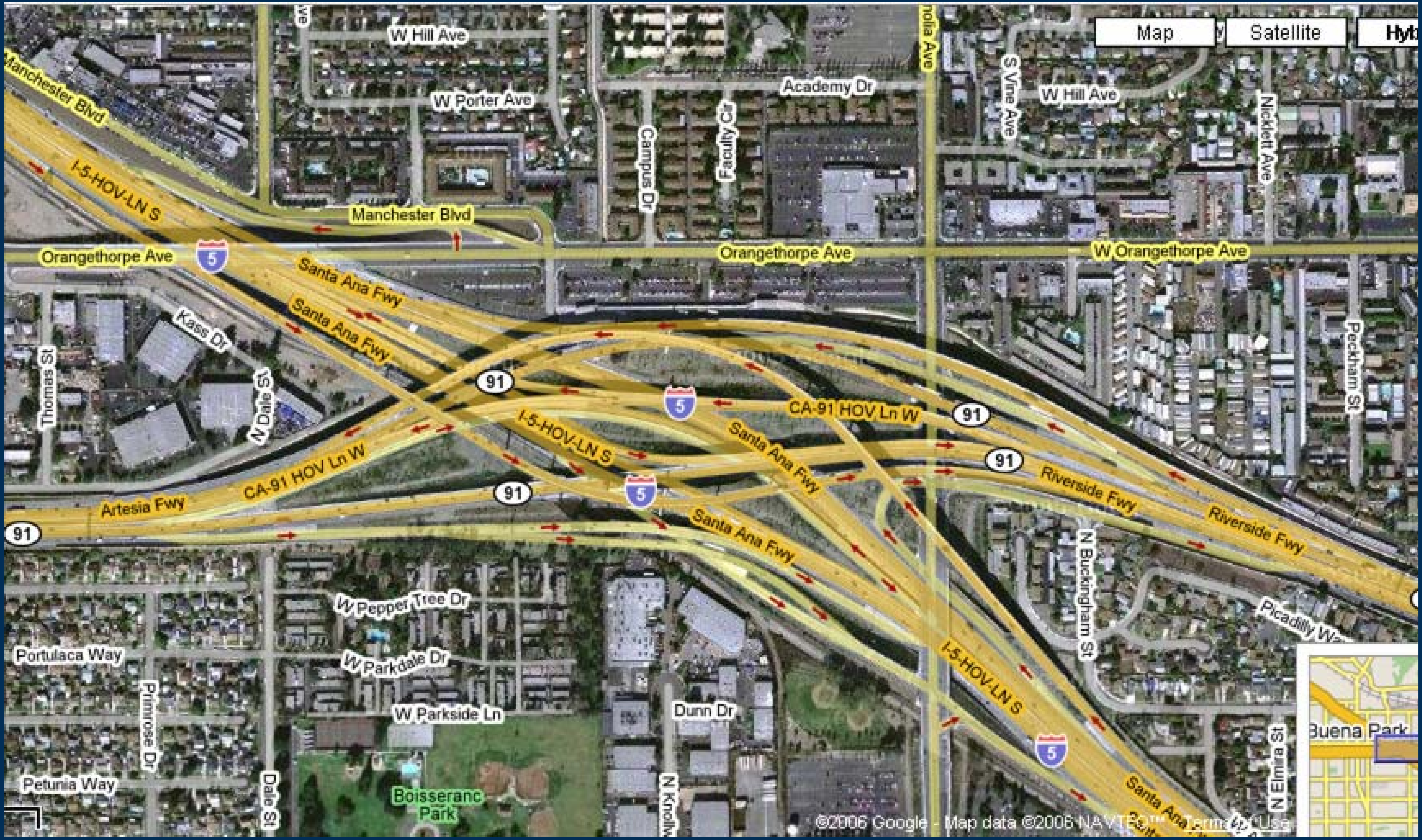


I-80 at Central St Interchange
North of Oakland, CA



SR-91 at I-5 Interchange

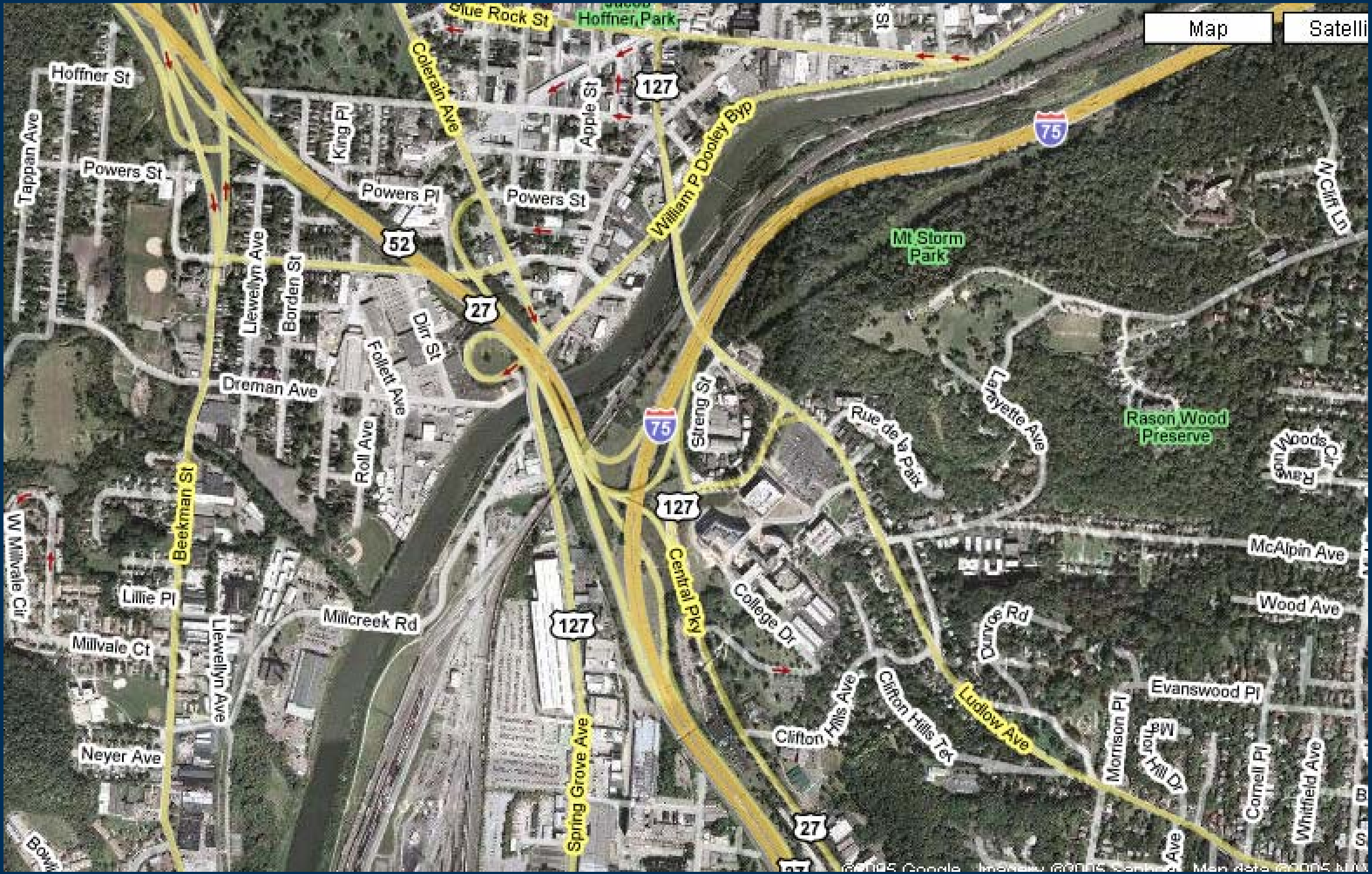
Los Angeles, CA



I-20 at Fulton Industrial Blvd

Atlanta, GA

I-75 at I-74 Interchange
Cincinnati, OH



I-880 at SR-238 Interchange
South of Oakland, CA

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SR-315 at I-70

Columbus, OH

I-93 at Columbia Rd Interchange

Boston, MA