Introduction of the New Nano Interchange Design as a Directional Freeway-to-Freeway Interchange

Jae-Pil Moon, Ph.D.
Post-Doc Fellowship Researcher
Korea Institute of Construction Technology
Goyang-Si, Republic of Korea 411-712
Tel. 82-31-910-0770, Fax 82-31-910-0161
Email: jpmoon@kict.re.kr

Joseph E. Hummer, Ph.D., P.E
Professor
Department of Civil, Construction, and Environmental Engineering
North Carolina State University
Raleigh, NC 27695-7908
Tel. 919-515-7733, Fax 919-515-7908
Email: hummer@ncsu.edu

and

Meredith H. Van Duyn, E.I.
Transportation Analyst
Kimley-Horn and Associates, Inc.
P.O. Box 33068
Raleigh, NC 27636-3068
Tel. 919-677-2108, Fax 919-677-2050
Email Meredith.vanduyn@kimley-horn.com

October 16, 2009
Word Count: 3,327text + 2,000 tables (4) and figures (4) = 5,327 total
Submitted for the 4th International Symposium on Highway Geometric Design
June 01-05, 2010

ABSTRACT

Freeway-to-freeway interchanges generally consume large amounts of right of way (ROW). Especially in dense urban areas of developing countries, attempts to limit the amount of ROW have contributed to system interchanges that are poorly designed and have capacity problems. Freeway designers need to provide drivers with large capacities while saving spaces in dense urban areas.

The nano interchange, a new system interchange, attempts to address this challenge. The nano interchange allows each of the four mainline freeway directions to occupy a different level. All ramps are then direct connections with one horizontal curve. This ramp arrangement can lead to shorter travel distances and lower amounts of ROW.

The authors designed example nano interchanges and comparable conventional interchanges with 35, 45, and 55 mph ramp design speeds. The comparison revealed that the nano interchange saves space for any given ramp speed and the construction plus right-of-way costs may not be much higher than the conventional interchange. However, the nano interchange appeared to have some problems based on the operational and safety evaluation conducted. Several modifications to the nano interchange are suggested to improve the design.

Key Words: nano interchange, conventional interchange, operation, safety, surrogate safety measure, construction cost, right of way

INTRODUCTION

The supply of freeways in urban areas across developing countries has generally not kept pace with traffic demand. Interchanges are essential components in freeway operations because they control freeway access and handle the movement of traffic between freeways. Since, in many cases, interchanges are inferior in design quality compared to the associated freeways and there are the likelihood of increased speed differentials between freeway mainlines and ramp junctions, the interchanges have contributed to operation and safety problems and to high fuel consumption. In addition, system interchanges also consume large amounts of right of way (ROW), especially in dense urban areas of developing countries, and attempts to limit the amount of ROW have contributed to system interchanges that are poorly designed and have the potential capacity problems. Freeway designers need to provide drivers with large capacities while saving space in dense urban areas.

There are many alternative forms for service (freeway to surface street) interchanges with four approaches. However, engineers have fewer choices where a four-approach system (freeway to freeway) interchange is needed. A directional four-level interchange is the most widely accepted in the United States as a system interchange without loops, shown in Figure 1.

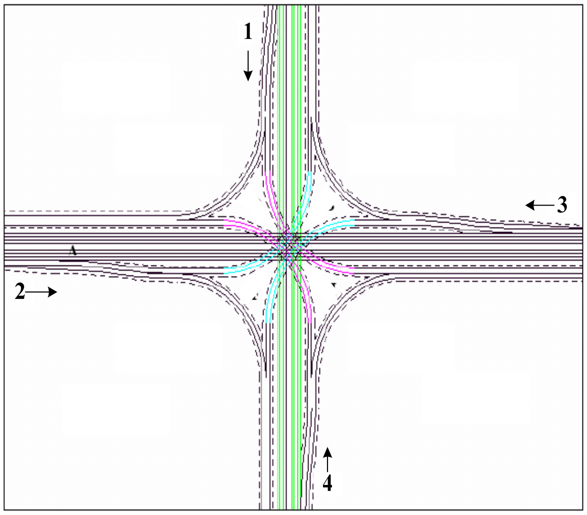

Figure 1 Four-level interchange

A few years ago, the second author of this paper (Dr. Joseph E. Hummer) began thinking about the challenge of addressing deficiencies in existing conventional system interchange design in dense urban areas, and he conceived a new system interchange design, the *nano interchange*. Specifically created with intentions of minimizing the amount of right of way (or the "footprint") needed for an urban interchange, the nano interchange may be an alternative design for densely populated and developed urban areas. Distinguishing design features of the nano interchange include direct connections for all movements, combination of left- and right-hand entrances and exits, and four levels of freeway and ramp structures.

A study is needed to evaluate if the innovative nano interchange will function well enough to compensate for its disadvantages, specifically in compact urban areas where real estate is precious and expensive. In this research effort, the capabilities and applicability of the new interchange will be estimated based on analyses of traffic operations, safety, construction costs, and right of way.

THE NANO INTERCHANGE CONCEPT AND DESIGN

A nano interchange is designed with the expectation that it would provide shorter travel distances, higher speeds, lower amounts of ROW, and higher levels of service compared to some other designs. The nano interchange design allows direct connections to be made because each freeway is in a double-deck configuration where one direction is at a higher elevation than the other. The most noticeable geometric characteristic of the nano interchange is that it uses direct connections for all the left turn and the right turn movements, made possible by the double-deck configuration. However, the nano interchange has some problems, such as: (1) confounding driver expectations by having left exits and entrances, because most drivers expect to have right exits and entrances; and (2) incurring high construction costs.

Figure 2 shows a schematic of the nano interchange types. Mainline 4 is on the highest level, with mainlines 3, 2, and 1 positioned accordingly from high to low, respectively. Figure 2 also shows the ramp configuration of the nano interchange; such that ramp 1→2 connects mainline 1 to mainline 2, etc. Figure 3 shows a three-dimensional geometric configuration of the nano interchange created in VISSIM. The reversed curve segment of a mainline freeway heading into the interchange is shown in Figure 4.

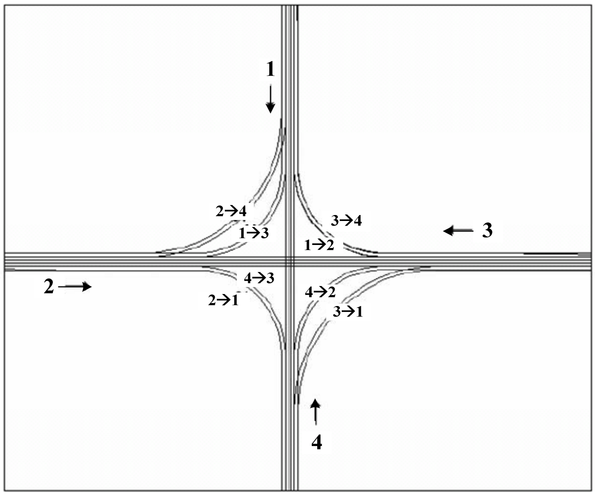

Figure 2 Plan view of a nano interchanges

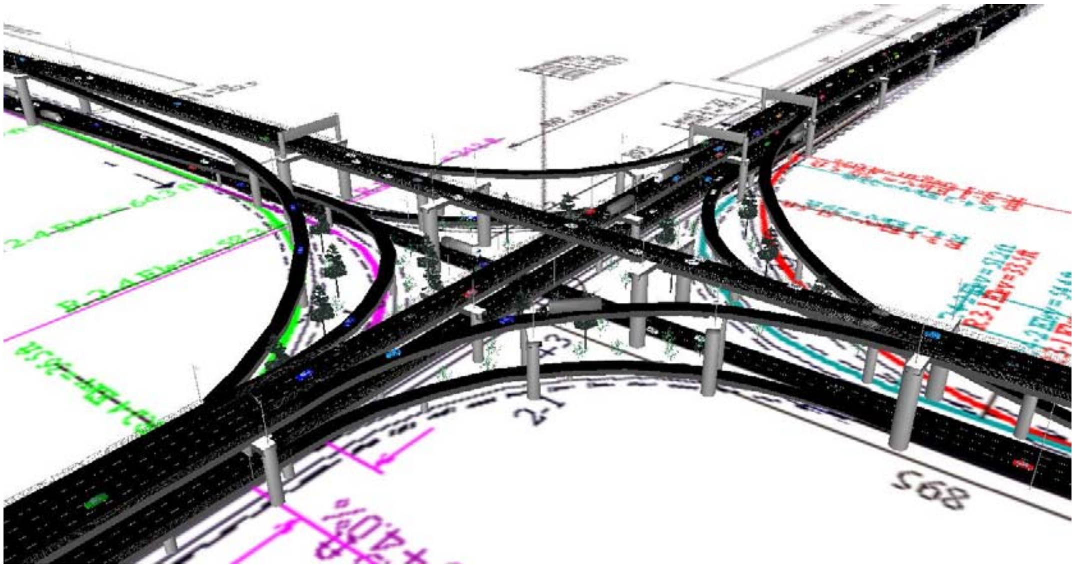

Figure 3 Three-dimensional view of a nano interchange

Figure 4 Reverse curve segment heading into a nano interchange

METHODOLOGY

Construction Costs and ROW Evaluation

To estimate construction costs and right-of-way needs, authors created and evaluated conceptual designs for the nano interchange and comparable conventional four-level interchanges. The designs needed to satisfy minimum design criteria in the American Association of State and Highway Transportation Officials' (AASHTO) 2004 *Policy on Geometric Design of Highways and Streets* [2] and in the 2002 North Carolina Department of Transportation (NCDOT) *Roadway Design Manual* [6]. Each interchange was designed for ramp speeds of 35, 45, and 55 miles per hour and was applicable to a compact urban area. Table 1 shows the common design criteria adopted for both types of interchanges. Acceleration and deceleration lanes for entrance and exit terminals were of the parallel type. Radii, grades, and speed-change lane lengths correspond to information in AASHTO for each ramp design speed.

Table 1 Typical Cross Section Design Elements

Design Element		Mainline	Ramp
Design Speed (mph)		70	35, 45, 55
Lane Width (ft)		12	16
Median Width (ft)		22	-
Shoulder Width (ft)	Left	10	10
	Right	10	12
Through Lanes		3	1
Maximum Superelevation		6 %	6 %

Since earthwork (fill) costs much less than using a structure, the deigns in this study primarily use fill rather than structure in an attempt to minimize cost. In particular, any point on level 3 or below not directly over another roadway was placed on fill. However, there is also a tradeoff between cost and right-of-way when using earthwork since fill required sideslopes, and bridges do not. Bridging generally decreases the design footprint but greatly increases the construction cost. It may also be desirable to build structures in certain situations (for example, to avoid environmentally sensitive features) despite the higher cost.

The right-of-way limit in these designs is considered to be the line at which the 2:1 slopestake gradient reaches level ground (an elevation of zero feet). Departments of transportation may consider the right of way line to extend past the slopestake line to account for utilities, sidewalks, or other infrastructure. However, since the designs presented in this document do not consider those items, the right of way limit and slopestake lines are synonymous.

Construction cost estimates were based on 2006 unit line-item provided by the NCDOT Design Estimates Unit, and will likely not be accurate for other places and times, although the relative costs between designs should not change much in other places and times.

Operation Evaluation

The purpose of this portion of the study was to evaluate ways that freeway-to-freeway interchanges perform operationally relative to each other under a variety of volume scenarios. The VISSIM model was selected to simulate the operations of the subject interchanges. VISSIM, which has been used and validated often recently, can realistically simulate merging or diverging maneuvers in the short spacing between left-hand and right-hand on-ramps or off-ramps in the nano interchange. Furthermore, VISSIM can more readily create the particular geometric configurations of the nano interchange than other simulations.

The four factors were varied in the operational analysis in this study: (1) mainline freeway volumes, (2) ramp volumes and directional distributions, (3) ramp design speeds, and (4) the percentages of heavy vehicles. The levels of traffic volume used for freeways were confined to two levels (6000 and 5000 vph), corresponding to LOS E and D, respectively. The volume levels of ramps also had two groups: 1000 and 1600 vph. Each ramp volume was also split into left-turn and right-turn movements by balanced or unbalanced proportions; the ratio of left-turn to right-turn movements for each volume level was set as 70 to 30, 50 to 50, and 30 to 70. The percentage of heavy vehicles across all the volume scenarios was set at either 10% or 20% to estimate the relative operational effects of heavy vehicles for each volume scenario on each interchange. Altogether then, there were five freeway mainline volume cases, two ramp volume cases, three turning movement ratios for the ramp volume cases, and two percentages of heavy vehicles, or 60 cases.

Before running the main experiments, sensitivity analysis was performed for the ways trucks and cars operate in VISSIM relative to various vertical and horizontal curves, and a calibration process was undertaken to insure that VISSIM behaved like the Highway Capacity Manual [4] in basic freeway segments and ramp sections.

Finally, the VISSIM model was run 15 times for one hour per run after a 5-minute warm-up for each combination of variables tested for each interchange type. Each replication used a different random number seed. All together, the number of VISSIM runs is calculated as follows: 30 volume scenarios × 2 heavy vehicle percentages × 3 ramp design speeds × 2 interchanges × 15 replications = 5,400 runs.

The operational analyses for each interchange were evaluated for an entire interchange in terms of four measures: 1) travel times (hours), 2) total delay (hours), 3) average speed (mph), and 4) travel times of ramp flows (hours). Also, the estimations of level of service (LOS) were conducted for key freeway segments such as basic freeway segments, merge segments, and diverge segments.

Safety Evaluation

Since the nano interchange does not exist, comparing all the alternative designs with actual numbers of collisions is not possible. One method is to obtain safety estimates was to employ surrogate safety measures to assess the safety of the traffic facilities. In this study, Surrogate Safety Assessment Model (SSAM) [8], developed by the Federal Highway Administration (FHWA), which performs conflict analysis by processing vehicles trajectory data extracted from micro-simulations, was adopted to make safety estimations. SSAM determines a collision probability based on individual vehicle positions, speeds, decelerations, and accelerations from a micro-simulation. Then, safety evaluations can be made through SSAM with vehicles trajectory data from the VISSIM models. SSAM identifies and classifies three conflict events--crossing, rear-end, and lane-change conflicts--according to the criteria for each vehicle-to-vehicle interaction.

The safety estimates were conducted for the whole interchanges with freeway through demand at 6,000 vph, ramp demand at 1,600 vph and 1,000 vph, and the heavy vehicle percentage of 10%, as one of the worst cases of the volume scenarios considered in the operation evaluation. Since there would not be large differences in safety effects between the alternative designs for the other volume conditions, corresponding to a high level of service C or D, the safety estimates were considered for the extreme volume case. Fifteen replications were performed to get the trajectory data for each design case and SSAM estimated surrogate safety measures with the pooled trajectory data.

RESULTS

The nano interchanges had the highest construction costs but required the least total acres of right of way, compared to the directional four-level interchanges of the same ramp design speed, as shown in Table 2. ROW savings for the nano over the conventional were from 15 to 33 acres. While the nano-interchange with a ramp design speed of 35 mph had the smallest right of way, it had the most expensive construction cost. However, in urban areas where population densities and property prices are very high, the construction plus right-of-way costs may not be much higher for the nano than the four-level.

Table 2 Construction Costs and Right of Way Estimates

Design Speed, mph	Construction Costs, Million $, 2006		Right of Way, acres	
	Conventional	Nano	Conventional	Nano
35	83	289	54	39
45	120	266	69	48
55	150	272	101	68

Table 3 shows differences in the interchange performance-related MOEs between the nano and conventional interchanges by ramp design speed and percentage of heavy vehicles. All the MOEs were averaged over all the volume scenarios for each interchange type. Generally, the entire interchange performances of the nano interchange are worse than those of the conventional interchange for each ramp design speed. For 10% heavy vehicles, differences in travel times and average speeds between the nano and conventional interchange diminish as ramp design speeds increase. Meanwhile, differences in delays increase as ramp design speeds increase. For 20% heavy vehicles, differences in the three MOEs between the nano and conventional interchanges are greater with an increase in ramp design speeds. The nano interchanges appear to have smaller ramp flow-related travel times than conventional interchanges.

Table 3 Comparing MOEs between Nano and Conventional Interchanges

MOE	Percent heavy vehicles, %	Ramp design speed, mph	Four-level	Nano
Travel Time (vehicle-hours)	10	35	851	860
		45	846	852
		55	834	840
	20	35	869	882
		45	863	878
		55	848	868
Speed (mph)	10	35	65	64
		45	65	65
		55	66	65
	20	35	63	63
		45	64	63
		55	65	63
Delay Time (vehicle-hours)	10	35	91	96
		45	87	93
		55	82	90
	20	35	107	116
		45	103	119
		55	95	118
Travel Time for Ramp Flows (vehicle-hours)	10	35	217	214
		45	211	208
		55	201	199
	20	35	224	219
		45	216	214
		55	205	205

The individual performance estimations indicate that the relatively poor interchange performance of the nano interchanges over the conditions tested are primarily due to turbulence in diverging influence areas, which are located in the rising grade segments, and in merging influence areas.

The operational results for the entire interchange as well as for individual segments show that conventional interchanges perform better than nano interchanges for all the volume scenarios tested. The primary operational problems of the nano interchanges for the tested volume conditions are as follows. First, the diverging influence areas of the nano interchange, located mostly on rising grades, generally cause the worst operational performance, as the compound effects of the geometric features and the poor climbing performance of heavy vehicles make the diverging maneuver more difficult. Second, the geometry of the ramp itself appears to affect the approach speeds of the ramp flows in some merging influence areas of the nano interchange. The operational results show that merging influence areas that connect to longer lengths and steeper grades of ramp appear to be inferior for average speeds, as compared to other merge influence areas. Third, as one of the geometric features of the nano interchange, the direct left-turn and right-turn ramps provide shorter travel distances for ramp flows. However, the short travel distances could not compensate for the inferior operational performances of the rest of the network as compared to the conventional interchanges.

It was expected that the lower the percentage of heavy vehicles, the better the operational efficiency of the nano interchange. Also, it should be noted that the traffic situations were simulated under the assumption that all exiting or entering vehicles were guided safely and made reasonable diverging or merging maneuvers. In the real world, left exits and entrances could cause some drivers to make erratic maneuvers. Specifically, because the nano interchange has left-hand exits and entrances, the nano interchange is more likely to have a higher potential for driver error than conventional interchanges. This factor thus could result in a poorer operational performance than the simulation results show.

Table 4 shows the number of each conflict type for each interchange type recorded using SSAM with a time to collision (TTC) equal or less than 1.5 seconds and maximum post-encroachment time (PET) equal or less than 5.00 seconds. These results indicate that while for the ramp volume of 1,600 vph, the number of conflict for the nano interchange is about 1.5 times higher than for the conventional interchange, there were not large differences in the number of the conflict between the two designs for ramp volumes of 1,000 vph. Further, the interchanges with the high ramp design speed appeared to have the lower probability of the conflicts than the low ramp design speed. Therefore, the surrogate safety measures provide evidence that as ramp and mainline freeway volumes increase, the nano interchange has high potential conflict points which can attribute to have an increase in the probability of collisions compared to the conventional interchange.

Table 4 Numbers of conflict estimated using SSAM

Ramp Volume, vph		Ramp Design Speed, mph	55		45		35	
		Interchange Type	Nano	Con.	Nano	Con.	Nano	Con.
1,600	Conflict Type	Total	609	465	692	463	701	509
		Rear-end	330	220	324	189	326	218
		Lane-change	279	245	368	274	375	291
1,000	Conflict Type	Total	392	339	479	316	474	367
		Rear-end	173	132	200	108	206	135
		Lane-change	219	207	280	208	268	232

CONCLUSIONS AND RECOMMENDATINS

The nano interchange, a new system interchange design, was introduced as one way to maintain mobility, efficiency, safety, and environment quality while requiring less right of way in dense urban areas where real estate is expensive.

The primary purpose of this study is to estimate the capability and applicability of nano interchanges in comparison to four-level conventional interchanges. This research consists of three tasks: (1) operational evaluation, (2) safety evaluation, and (3) construction cost and right of way evaluation. As a result, the new system interchange design required the lower total acres of right of way, compared to the conventional interchange, saving 15 to 33 acres of right of way. Although the nano interchange may not necessarily work in low-to-medium density urban environments, it may be suitable for construction in other locations around the world – such as Mexico City, Seoul, Shanghai, or Mumbai – where the high cost of ROW would outweigh the higher construction costs for the nano.

The VISSIM and SSAM results above showed that the nano interchange had operational and safety disadvantages relative to a conventional four-level interchange with the same ramp design speed. In addition to the identified problems, there are other important issues associated with the nano interchange that would have to be resolved before one was built, such as: (1) constructability, (2) environmental impacts, (3) driver expectations, (4) compatibility with adjacent interchanges, (5) signage, and (6) the specifications of the structural design. Modifications to the nano interchange idea are possible to improve the problems identified for the nano interchange. For instance, it may be possible to convert all the left-hand ramps to right-hand ramps while retaining the nano interchange concept. Although this research showed that there are certain disadvantages with the current nano interchange design, the nano interchange concept should still be considered by transportation engineers and planners who are looking for new design ideas for dense urban areas.

ACKNOWLEDGEMENTS

The authors are grateful for the funding they received from the Southeastern Transportation Center to support this work.

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