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A Staggered-Diamond Design for Automated/Manual-HOV Highway-to-Highway Interchange

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EXECUTIVE SUMMARY

The concept of automated highway systems (AHS) was motivated primarily by its potential for large capacity and safety gains ***without*** requiring significant right-of-way acquisition. However, it may require a significant amount of modification to the current highway infrastructure. Particularly acute is the issue of providing the infrastructure needed to support continuous automated driving from one highway to another. Tsao et al. pointed out that eight extra highway-to-highway connector ramps, in addition to the eight existing highway-to-highway connector ramps for the conventional manual traffic, are required if continuous automated driving (through the interchange) is to be supported for all automated traffic approaching the interchange. The potential of AHS can nor be fulfilled without such automated connector ramps. However, expanding the interchange infrastructure to accommodate the eight automated connector ramps, in addition to the eight existing conventional ramps at a location with high geometric complexity already, could be very complex and difficult. Furthermore, additional **right-of-**way could be required. The complexity and the difficulty may severely constrain the design and operation of an AHS and the evolution of the current highway systems towards the AHS.

Recognizing the importance of supporting continuous automated driving at the interchanges and the potential complexity of design, this paper first proposes a ***staggered-diamond*** design for the eight additional connector ramps for AHS. The design requires only ***four,*** instead of eight, separate structures, each supporting two-way traffic. This paper then discusses the constraints of this design on the conceptual design and evolution of AHS. Note that the constraints would be much more acute if the proposed staggered-diamond design is replaced by eight separate structures, each supporting only one-way traffic.

Many variations of this design exist. The idea of consolidating two ramps carrying traffic of opposite directions into one physical structure is robust enough for various geometric configurations and limitations. This design greatly reduces the structural complexity of the eight separate connector ramps and increases the feasibility of AHS. The major requirement is the availability of a wide-enough median, but only at the interchange.

The staggered-diamond is also applicable to the design of eight ***additional*** highway-to-highway connector ramps directly connecting the HOV lanes on two crossing highways (assuming that the HOV lane is adjacent to the median). Note that, as in the case of AHS, the potential of HOV-lane concept can ***not*** be fulfilled without such HOV highway-to-highway connector-ramps. The provision of such HOV connector ramps could considerably speed up the HOV traffic and could be a significant additional incentive for ridesharing. The proposed design also increases the feasibility of a freeway shuttle van service, proposed by Tsao as the initial AHS deployment target.

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(1) INTRODUCTION

(1.1) The Objectives of AHS

The concept of automated highway systems (AHS) was motivated primarily by its potential for large capacity and safety gains ***without*** requiring significant right-of-way acquisition. Automated driving has been interpreted as "hands-off' and "feet-off' driving. Operation in a freeway type of roadway has been assumed. The key areas for performance improvement, as stated in the Broad Agency Announcement (BAA) for the FHWA Precursor System Analysis of Automated Highway Systems [FHWA, 1992], are: safety, throughput, user comfort and environmental impacts. Recently, Bishop et al. [Bishop et al., 1994] argued for the necessity to include moving ***people,*** as opposed to moving just vehicles (in terms of the number of passing vehicles per lane per hour), as an additional performance objective for AI-IS. While expressing confidence in the enabling technologies, they emphasized the importance of ***systems*** issues and research. To facilitate AHS deployment, they also suggested a shift from the previous impetus of technology-push to a market-pull strategy.

(1.2) AHS Design and Deployment Challenges

In a recent comprehensive treatment of conceptual AHS design, Stevens [Stevens, 1993; Stevens, 1994] discussed AHS deployment and operations goals, analyzed AHS characteristics and identified 37 alternative AHS concepts. With a narrower scope, Tsao et al. [Tsao et al., 1993] recently identified many major design options and issues for operating fully automated AHS. They also addressed the impacts of the options on major AHS performance criteria including safety, capacity, human factors, infrastructure, cost, etc. Because of the many options for operational design, there exist a large number of possible operating scenarios for a mature AI-IS. The dimension of evolution leads to an even larger number of possible AI-IS evolutionary scenarios. However, AHS operational design and evolution also involves a large number of potential issues and constraints. (See [Hall and Tsao, 1994; Al-Ayat and Hall, 1994; Tsao, 19951.)

(1.3) Focus on Highway-to-Highway Interchange for Continuous Automated Driving from One Highway to Another

Among the many potential issues and constraints, we focus on those regarding infrastructure in this paper. Although an AHS may not require a significant amount of right-of-way acquisition, it may require a significant amount of modification to the current highway infrastructure. Although a completely new network that is dedicated to the automated traffic and independent of the current highway network is in theory possible, we focus on those AHS that are essentially confined to the existing right-of-way. Major infrastructure types include (i) grade-elevated roadways dedicated to the automated traffic, (ii) non-elevated but isolated lanes dedicated to the automated traffic, and (iii) non-elevated, non-isolated but dedicated automated lanes (with a transition lane between the automated lanes and manual lanes). This paper focuses on the latter two types. In both types, automated lanes are assumed to be the inner lanes, i.e. the left-hand lanes with respect to the flow of traffic.

Many potential issues regarding AHS infrastructure support and highway evolution have been identified in the literature [Tsao et al, 1993]. Particularly acute is the issue of providing the infrastructure needed to support continuous automated driving from one highway to another at the interchange between two crossing highways. Tsao et al. [Tsao et al., 1993] pointed out that ***eight*** extra highway-to-highway connector ramps, in addition to the eight existing highway-to-highway connector ramps for the conventional manual traffic, are required if automated driving is not to be disrupted during the process of highway-change, i.e. moving from an automated lane of one highway to an automated lane on the crossing highway. (Two ramps are needed for each of the four approaches to the interchange, one for connecting to one direction of the crossing highway and the other for connecting to the opposite direction of the crossing highway.) Expanding the current interchange infrastructure to accommodate these eight additional automated connector ramps at a location which already features high geometric complexity could be very complex and difficult. Moreover, additional right-of-way could be required. Accommodating such additional complexity may severely constrain the operational design of an AHS as well as the evolution of the current highway systems towards an AHS.

Since a highway-to-highway interchange requires one of the most complex construction tasks in a highway system, the viability of an AHS infrastructure design could be challenged at such interchanges, e.g. the design option of an isolated network of elevated structures over the current right-of-way for automatic traffic. If elevation, in such an elevated system, is also required at the interchanges too, then four layers of roadway are necessary at the location where the two highways cross each other. In such a case, the construction complexity and the evolution difficulty may be exceedingly high.

To avoid excessive reference to the qualifier “highway-to-highway” in the terms “highway-to-highway interchange” and “highway-to-highway connector ramp”, we simply ***use the*** terms ***interchange*** and ***connector ramp*** respectively for simplicity.

(1.4) Purpose and Organization of the Paper

Recognizing the importance of supporting continuous automated driving at the interchanges and the potential complexity of infrastructure design/evolution, this paper proposes, at the level of concept definition, a ***staggered-diamond*** design for the eight automated connector ramps for AHS. The design requires only ***four,*** instead of eight, additional separate physical structures, each supporting two-way traffic. This design significantly reduces the infrastructure complexity and hence increases the feasibility of AHS. Even with the reduced complexity and increased feasibility, the need to support automated highway-change still imposes a number of constraints on AHS operational design and evolution. These constraints will be identified and examined.

This paper is organized as follows. Section 2 introduces the staggered-diamond design for automated connector ramps and discusses the main features of this design. Section 3 discusses the constraints on AHS operational design imposed by the requirement for continuous automated highway-to-highway driving. The constraints on AHS evolution due to the same requirement are discussed in Section 4. Section 5 concludes this paper.

(2) A STAGGERED-DIAMOND DESIGN FOR EIGHT AUTOMATED HIGHWAY-TO-HIGHWAY CONNECTOR RAMPS

We first note that automated highway-to-highway driving in a mature AHS is desirable from the driver's perspective and is crucial at those interchanges where the demand for highway-change by the automated traffic is large. The desirability of a mature AHS without it is significantly reduced. We now argue as follows. Suppose that such automated driving is not supported at all highway-to-highway interchanges.

If the primary target users are automobiles, then the driver needs to switch between the automated and manual driving modes at each interchange. This could be annoying, even if such transitions incur no difficult tasks for the driver. Now also assume that the deployment of such an automobile-oriented AHS increases the highway capacity considerably and a comparable increase in demand results. Then, the highway-changing traffic at an interchange may also increase considerably. The additional amount of (manual) lane changes for highway-change at an interchange may lead to significant amount of additional traffic congestion. The congestion may occur even if the manual connector ramps have been sufficiently augmented to accommodate the additional highway-changing traffic.

If the primary target users are buses, then a driver must be on-board taking over manual control for highway-changes. We also note that, to support continuous automated highway-to-highway driving, provision of eight additional connector ramps is necessary whether or not the automated traffic is isolated from the manual traffic and whether or not the isolated roadway is elevated.

Before defining the concept of a staggered-diamond design, we state (i) the types of AHS infrastructure for which the design is intended and (ii) the assumptions about the supporting automation technologies.

(2.1) Applicable Infrastructure Types

We focus on the following two infrastructure types:

(11) non-elevated roadway with physically isolated lanes, consecutive and adjacent to the median, dedicated to the automated traffic;

(12) non-elevated roadway with dedicated automated lanes, consecutive and adjacent to the median, and a transition lane between the automated lanes and the manual lanes.

A major difference between these two is that the former segregates completely the automated traffic from the manual traffic with physical barriers while the latter does not. The former is effectively a new highway network dedicated to automated traffic. In both cases, the automated lanes are assumed to be the inner lanes, i.e. the left-hand lanes with respect to the flow of traffic.

(2.2) Assumptions: Supporting Automation Technologies and Space Availability

We make the following assumptions:

(Al) Traffic merging at the point of lane merge and traffic diverging at the point of lane drop are both automated. Due to the complete segregation in the former case, on-ramps and off-ramps dedicated to automation-equipped vehicles wishing to use the automated lanes are required. We assume that these on-ramps and off-ramps are instrumented so that both the required merging of the entering vehicles into the existing traffic and the required diverging of the exiting traffic are performed automatically by the vehicles and the roadside control system without manual control.

(A2) The space required by such a design is or can be made available, particularly a median at the interchange that is wide enough to accommodate (i) two lanes of **traffic,** (ii) the physical barriers in the middle and (iii) two walls on the edge.

(2.3) The Staggered-Diamond Design

The main idea of the design is to consolidate the two ramps ***carrying*** traffic of exact opposite directions into one physical structure, called ***dual (connector) rump.*** This reduces the required separate structures from eight to four. This is possible because, unlike the conventional connector ramps, the automated connector ramps connect the leftmost lane(s) of one highway to that (those) of another, which are all adjacent to the median. Staggering is needed for separation of entry/exit points and for proper height clearance.

Consider a perpendicular crossing of two highways (overpassing highway and underpassing highway) and focus on any one of the four “branches”. To allow exit/entry of traffic to and from the two different directions of the crossing highway, the landing points of the two dual ramps on this branch should be apart. To provide sufficient height clearance, both of the two dual ramps should ascend high enough above the ground level before they can extend over any of the two highways. Furthermore, sufficient height clearance between two overlapping dual ramps, if any, is also required. A high barrier is erected to isolate the traffic of opposite directions. The exact dimensions of this design depend on AHS operational requirements, vehicle capabilities, construction constraints, and site-specifics and are beyond the scope of this paper. Figure 1 illustrates the design with a two-dimensional bird's-eye view. Figure 2 focuses on a particular branch.

Given the height clearance of the dual ramps with respect to the two highways, the new staggered-diamond structures have sufficient clearance with respect to the conventional connector ramps. In this sense, the staggered-diamond and the clover-leaf are independent and non-interfering. Since the dual ramps are away from the "center" of the interchange, i.e. the exact location where the two highways cross each other, the height of the new structures is no more than the elevation of the overpassing highway plus the required ramp clearance. In fact, the height could be significantly less than this upper bound.

The idea of consolidating two ramps carrying traffic of opposite directions into one physical structure is robust enough for various geographical configurations and limitations as long as the assumptions are satisfied. The robustness comes from the simplicity of the design. Despite its conceptual simplicity, this design greatly reduces the structural complexity of the eight separate connector ramps. The major requirement is that a wide-enough median is or can be made available (e.g. by offsetting the manual lanes to the shoulders to widen the median or by widening the interchange area), but ***only*** at or near the interchange.

The idea is basically to connect the four pairs of the adjacent medians of the four branches at the interchange. Note that there exist variations to this design. Also note that, with the height dimension suppressed, the design shown in Figure 1 is symmetric with respect to both highways. There exist non-symmetric variations to this design. Consider the following example. Assume that the underpassing highway at the interchange is on a level ground and that the overpassing highway is grade-elevated. Since the overpassing highway is elevated, the highest point of the dual ramp is near the overpassing highway and could be as high as the elevation of the overpassing highway plus the required clearance for the ramp (i.e. double elevation). The maximum height of this dual ramp can be reduced by having the dual ramp overlap vertically with the overpassing highway as far out from the crossing location (of the two highways) as possible. However, this may require longer ramps.

(3) POSSIBLE CONSTRAINTS ON AHS OPERATIONAL DESIGN

Even with the reduced number of separate structures for supporting continuous automated highway-to-highway driving, the following issues may still constrain AHS design and deployment. Note that they would be much more acute if the staggered-diamond design is replaced by eight separate ramps.

(3.1) Space Requirement and Complexity/Cost of Construction

We note that if driving during highway-change is to be automated, building dual ramps could be the most efficient way, in terms of construction complexity and cost. But, this construction could still be too complex or costly. Moreover, this design hinges upon the availability of a median that is or can be made wide enough to accommodate two lanes of traffic plus the required barrier in the middle and the two walls on the edge. This requirement may not be satisfiable for all interchanges. Now, assume that this median cannot be made available. If only a space large enough to accommodate one lane plus the required walls on the two edges can be made available on both highways, then eight separate ramps, at least separate at the level of median, will be required and hence the construction may be more complex and costly. If such a space cannot be made available, then accommodating continuous automated highway-to-highway driving could be very difficult.

(3.2) Difficult Accommodation of Multiple Automated Lanes on Staggered-Diamond

Although accommodating multiple lanes (each direction) on a dual ramp could be desirable, it requires a significantly wider median at the interchange as well as a bigger structure. Either of the two requirements may be undesirable enough and may limit the number of lanes on a dual ramp. If eight separate ramps, each carrying multiple lanes of traffic of a common direction, are to be built, the construction could be very complex and costly, more so than the construction of single lane ramps.

(3.3) Incompatibility of Dedicated Automated Lane and Manual HOV Lane on Staggered-Diamond

If the automated lanes are physically isolated from the manual lanes, including the manual HOV lanes, then continuous highway-to-highway manual HOV driving is most likely impossible. Suppose now that the automated traffic is not physically isolated from the manual traffic. Also suppose that the left-most lane is dedicated to automated traffic (i.e. no manually-driven vehicles are allowed) and the adjacent lane (transition lane) is designated as the lane on which automation-equipped vehicles switch between manual and automated driving modes. Furthermore, a manual HOV lane is next to the transition lane. (The manual HOV lane is dedicated to use by manual high-occupancy vehicles and automation-equipped vehicles on their way to the automated lane.) Under these assumptions, manual HOV traffic cannot reach the median and hence provision of dual ramps cannot benefit the manual HOV traffic in terms of separation from “low-occupancy-vehicle” traffic. If manual HOV traffic is allowed on the automated lane and the transition lane only for reaching the dual ramps at or near an interchange, then the manual HOV traffic can benefit from the dual ramps. However, mixing manual traffic with automated traffic may be unsafe and the achievable capacity may be significantly lower than what may have been achievable otherwise.

(3.4) Difficult Accommodation of One Dedicated Lane for Each Type of Automated Vehicles on AHS

It may be desirable that multiple types of vehicles, e.g. automobiles, vans, buses and trucks, can be accommodated on AHS and that each type of vehicle travel on lanes dedicated to only that particular type of vehicle. However, it is difficult to imagine that such accommodation can be provided on an AHS without mixing different types of vehicles in one lane throughout the whole highway system. Such mixing is required at least when a vehicle is in the process of reaching the designated lanes from the entry point or in the process of reaching the exit point from the designated lanes. At an interchange, some merging and mixing of different types of automated traffic is required if different types of automated traffic are allowed to use the dual ramps. It is likely, if not certain, that such mixing is required on the dual ramps. Such mixing (or merging) of different types of automated traffic may impact safety, perceived safety, capacity, operational complexity, etc.

(4) POSSIBLE CONSTRAINTS ON AHS DEPLOYMENT

We now briefly discuss some possible constraints related to AHS deployment. Again, these constraints would be only more severe if the staggered-diamond design is replaced by the eight separate ramps.

(4.1) Smaller Market Penetration without Automated Highway-to-Highway Interchanges

Suppose that the AHS is targeting the automobiles as the primary users. Also assume that AHS requires a significant amount of infrastructure support and modification. Without extensive infrastructure modification, not much driving can be automated and hence market penetration could be difficult. But, without sizable market penetration, it is not cost-efficient to build the dual ramps. After considering seven categories of constraints on initial AHS deployment, Tsao [Tsao, 19941 recently proposed a freeway shuttle van service for AHS debut.

Construction of highway-to-highway connector ramps and other infrastructure modifications can grow gradually with the expansion of that type of service. When the infrastructure is extensively modified, automobile purchasers could then be enticed to purchase the automation options. (From the view point of AHS deployment, the staggered-diamond structures can be built to benefit the manual HOV traffic prior to the deployment of AHS. This could be an important incentive to increase ridesharing.) Without the convenience of continuous automated highway-to-highway driving, market penetration could be smaller.

(4.2) No Automobile Automation Before Provision of Dual Ramps

Suppose again that the AHS is targeting automobiles as the primary users. Also suppose that, despite the absence of automated highway-to-highway interchanges, the market penetration is high. Then, considerable increase of traffic congestion at interchanges is likely, due to the large increase of lane changes (from the left-hand lanes to the manual connector ramps on the right-hand side) resulting from the likely large increase of highway-changing traffic. Note that the congestion is likely even if the manual connector ramps have been sufficiently augmented to accommodate the additional highway-changing traffic.

(4.3) Traffic Disruption During Construction and Provision of Temporary Lanes during Construction

The geometry of a conventional interchange is already complex and the traffic flow is subject to a number of possible types of disturbances. Therefore, disturbance to the existing traffic during dual-ramp construction should be minimized. Advanced construction technologies and/or temporary lanes during construction may be required. These may be difficult and/or costly.

(4.4) Un-acceptability of Manual HOV Deprivement for AHS

Suppose that the four dual ramps are constructed to benefit the manual HOV traffic prior to AHS deployment. Then, depriving this benefit for AHS deployment may not be easily accepted unless the AHS accommodates transit vehicles and only automation-equipped HOVs are allowed to use the dual ramps. However, if, for some reason, further AHS deployment stops after its initial introduction, then the four dual ramps at an interchange remain useful. This significantly reduces the risk of wasting public funds.

(5) CONCLUSION

This paper proposed a staggered-diamond design for the automated highway-to-highway connectors ramps at an interchange. Many variations of this design exist. Although a perpendicular crossing has been implicitly assumed, the idea of consolidating two ramps carrying traffic of opposite directions into one physical structure is applicable to non-perpendicular crossings as well as “T-shaped” interchanges. Modification of design is required where highway crossing is not perpendicular or is constrained by geography or geometry. But, the main features of this design remain intact. When the required space for a dual ramp cannot be made available at the median but a space large enough to accommodate one lane plus the required walls on the two edges can be made available, the dual ramp has to be separated into two structures at the median.

The staggered-diamond is also applicable to the design of eight ***additional*** highway-to-highway connector ramps directly connecting the manual HOV lanes on two crossing highways (assuming that the manual HOV lane is adjacent to the median). Since highway-to-highway interchanges tend to create the most serious traffic bottlenecks, the potential of (manual) HOV concept can ***not*** be fulfilled ***unless*** the ridesharing public can avoid the traffic congestion at these highway-to-highway interchanges. The provision of such manual HOV connector ramps could considerably speed up the manual HOV traffic and could be a significant additional incentive for ridesharing.

When applied to interchanges in an AHS with elevated infrastructure, the idea of consolidating two ramps carrying opposite traffic into one physical structure (connecting the two elevated medians) can also reduce the number of separate structures from eight to four. At those interchanges where existing geometry does not allow above-ground construction of four separate structures, the consolidation idea could also reduce the number of separate tunnels from eight to four. Highway interchange design is site-specific. The proposed staggered-diamond design offers an additional alternative to the highway designer for use in addressing specific situations.

A major assumption for the design is the availability of a median at the interchange (and ***only*** at the interchange) that is or can be made wide enough to accommodate two lanes of traffic plus the barriers in the middle and the two walls on the edges. Assuming that an automation-equipped vehicle transitions into the automated driving mode on the on-ramp and traffic merging at the end of an on-ramp is fully automated, then medians, if existing, can be used to provide direct access to and egress from the dedicated automated lanes to city streets. The idea of such median-reaching on-ramps is particularly useful if additional lanes need to be converted into automated lanes as highway automation gains more popularity. With such on-ramps, converting additional lanes for automated traffic does not require any modification to the on-ramps. This is in contrast with the four entry/exit designs proposed by Varaiya [Varaiya, 1994].

Possible constraints on AHS operational design and evolution associated with the need to provide continuous automated highway-to-highway driving were also discussed. We remark that those possible constraints would only become much more acute if the staggered-diamond design is replaced by eight separate ramp structures.

This staggered-diamond design significantly increases the the practicality of the infrastructure required for AHS and hence the feasibility of AHS. Tsao [Tsao, 1994] proposed a freeway shuttle van service as the initial AHS deployment target. This design enables the continuous automated van/bus driving from the on-ramp at the origin activity center to the off-ramp at the destination activity center. If, at an advanced deployment stage, the proposed shuttle van can be operated safely without the supervision of a driver, then, with the support of the automated highway-to-highway connector ramps, the driving required between the two activity centers can be completely automated without the attendance of a driver. This has the potential of reducing significantly the labor cost.

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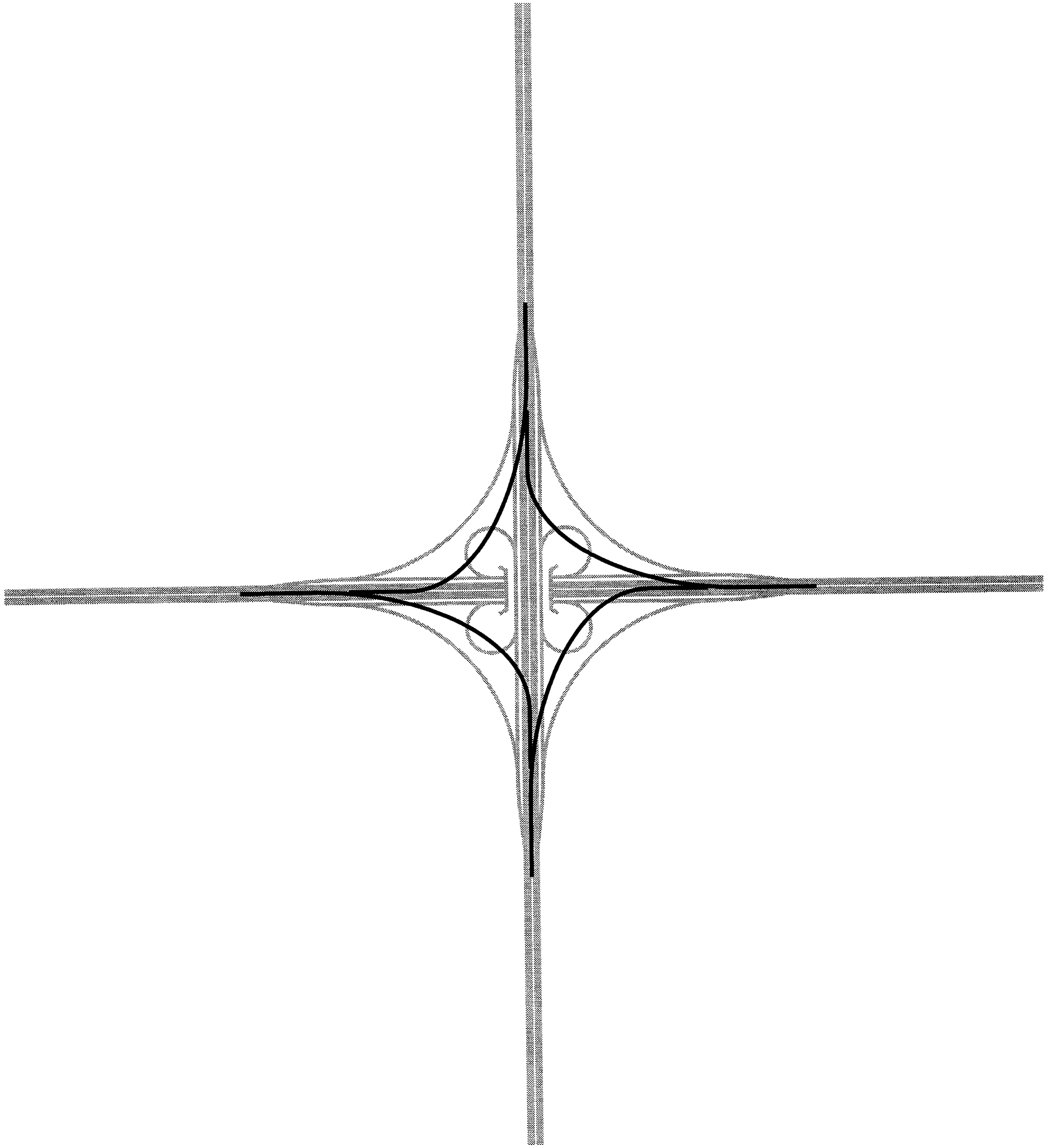

Figure 1. A Bird's-Eye View of the Staggered-Diamond Design.

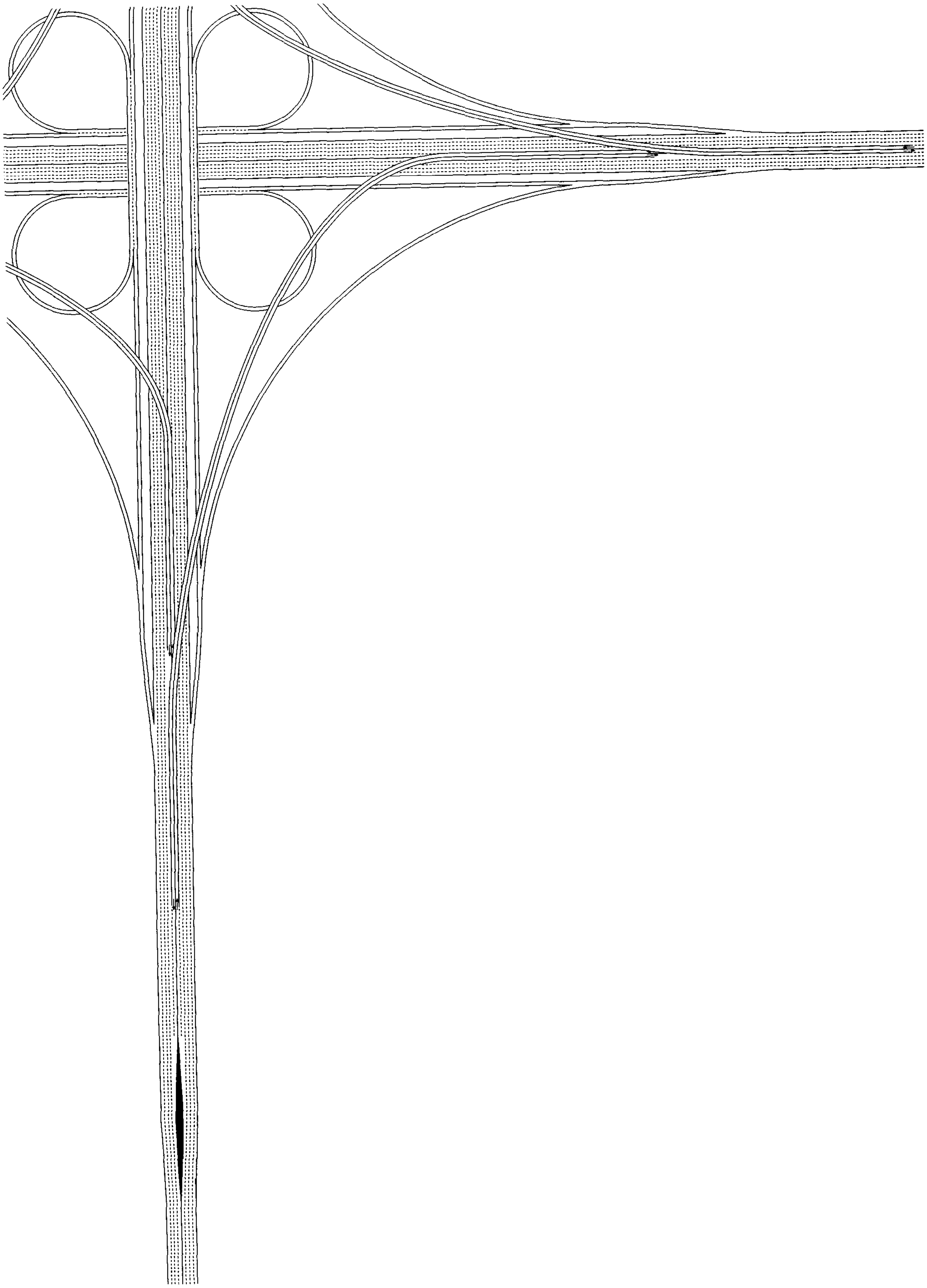

Figure 2. A Bird’s-Eye View of a Dual Ramp.