Alignment Design of Underground Road: A Simulator Study

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Abstract: In order to study the linear combination design method of underground roads, a road model with 16 test sections was designed for 8 common horizontal and vertical line combinations, and two test environments, up and under ground, were built. Fifteen participants participated in the driving simulation experiment. Driving behaviors between different lanes of roads on-ground and underground roads of each test section, each section with up or down slopes and with left or right turns were compared and analyzed. Then the applicability of different horizontal and vertical line combination in underground road design was evaluated.

1. Introduction

The road alignment is a three-dimensional linear shape formed by a curve and connecting straight line, the linear shape was determined by horizontal-vertical section and cross-section, which seriously affects the safety of vehicle driving. Road designers and researchers have been exploring road alignment design indicators, especially flat and vertical alignment indicators, with a view to constructing safer and more pleasant roads. For example, when designing road alignments, flat-clad and vertical solutions should be selected as much as possible. These mature research results have been included in the road alignment design standards of various countries and used to guide the road alignment design.

With the rapid development of road construction in the world, especially in developing countries, underground roads have developed rapidly in recent years. On the one hand, highways have begun to extend to mountainous areas, and more and more tunnels have been opened to traffic; while on the other hand, road construction must develop to underground because of urban development has been affected by land using. Now more urban interchanges and underground roads have begun to be constructed and put into use. However, compared with on-ground roads, research on the alignment design indicators of underground roads were lack, designers do not have separate design standards to refer when designing. Due to its unique enclosed environment and restricted view conditions, the driving environment of underground roads is quite different from that of general ground roads, which determines that its linear index has higher requirements than ground roads. In order to meet the construction needs of actual projects, it has become an urgent task to carry out research on the alignment design index of underground roads and put forward the safety design method of the underground road alignment.
This article focuses on eight horizontal and vertical line combinations, based on driving simulation experiments, analyzes and contrasts the differences of driving behavior on-ground and underground roads, and advantages and disadvantages of different horizontal and vertical line combinations and their applicability on underground roads were discussed.

2. Research road design
As shown in Figure 1, the schematic method is used to exhaust 13 horizontal and vertical line combinations, among which:

1. Combinations A and M are similar, with vertical and horizontal curves crossing, crossing straight lines and transitional curves;
2. Combinations B and K are similar, the vertical curve crosses the horizontal curve, and crosses the straight line, the gentle curve and the circular curve;
3. Combinations C and I are similar, the vertical curve crosses the horizontal curve, and crosses the straight line, the transition curve, the circular curve and the transition curve;
4. Combination D is the case of vertical packing, which will not be used in the design;
5. Combinations E and L are similar, the flat wrap is vertical, and the vertical curve is in the transition curve. In this case, the length of the vertical curve will be short, and the design is not used much;
6. Combinations F and J are similar, flat and vertical, and the vertical curve lies in the easement curve and the circular curve;
7. Combination G is flat and vertical, the vertical curve is located in the middle of the horizontal curve, and it spans the transition curve, round curve and transition curve, which is a good combination;
8. Combination H is flat and vertical, and the vertical curve is inside the circular curve.

Since the road runs in both directions, this study selects 8 linear combinations, including combinations A, C, E, F, G, H, K, and M as the research objects. At the same time, in order to minimize the interference of irrelevant factors, the same linear index is adopted, that is, the radius of the horizontal curve used in the research is 800m, the length of the easement curve is 120m, the length of the curve is 159.25m, and the up and down slope is ±3.5%.

![Figure 1: Schematic diagram of different linear combination schemes](image)

Taking into account the difference between the left and right turning of horizontal curve, and up and down slope, two sections were designed for the vertical curve in the 8 linear combination schemes. Finally, there are 16 experimental sections. The design parameters are shown in Table 1. The road sections are connected by straight lines, and a road route with a length of 25.15km is finally designed.
### Table 1 Alignment index of the road combination for research

| Section NO. | First transition curve | Curve midpoint | Second transition curve | Vertical Curve Combination |
|-------------|------------------------|----------------|-------------------------|----------------------------|
|             | Starting point | End point | Starting point | End point | Change point | Type | Curve radius | Tangent length |
| 1           | K4+798.817   | K4+918.817 | K4+998.443 | K5+078.07 | K5+198.07   | Concave | 3000 | 52.5 | A             |
| 2           | K5+795.705   | K5+915.705 | K5+995.331 | K6+074.958 | K6+194.958 | Concave | 10000 | 175 | C             |
| 3           | K6+922.593   | K6+912.593 | K6+992.219 | K7+071.846 | K7+191.846 | Concave | 2500 | 43.8 | E             |
| 4           | K7+789.48    | K7+909.48  | K7+989.106 | K8+068.733 | K8+188.733 | Concave | 5000 | 87.5 | F             |
| 5           | K8+786.507   | K8+906.507 | K8+986.994 | K9+056.621 | K9+185.621 | Concave | 9000 | 157.5 | G             |
| 6           | K9+783.255   | K9+903.255 | K9+982.881 | K10+062.508 | K10+182.508 | Concave | 2500 | 43.8 | H             |
| 7           | K10+780.143  | K10+900.143 | K10+979.769 | K11+059.396 | K11+179.396 | Concave | 8000 | 140 | K             |
| 8           | K11+777.03   | K11+897.03 | K11+976.656 | K12+056.283 | K12+176.283 | Concave | 3000 | 52.5 | M             |
| 9           | K12+773.918  | K12+893.918 | K12+973.544 | K13+053.171 | K13+173.171 | Concave | 3000 | 52.5 | A             |
| 10          | K13+770.806  | K13+890.806 | K13+970.432 | K14+050.059 | K14+170.059 | Concave | 10000 | 175 | C             |
| 11          | K14+767.693  | K14+887.693 | K14+967.319 | K15+046.946 | K15+166.946 | Concave | 2500 | 43.8 | E             |
| 12          | K15+764.581  | K15+884.581 | K15+964.207 | K16+043.834 | K16+163.834 | Concave | 5000 | 87.5 | F             |
| 13          | K16+761.468  | K16+881.468 | K16+961.094 | K17+040.721 | K17+160.721 | Concave | 9000 | 157.5 | G             |
| 14          | K17+758.356  | K17+878.356 | K17+957.982 | K18+037.609 | K18+157.609 | Concave | 2500 | 43.8 | H             |
| 15          | K18+755.243  | K18+875.243 | K18+954.869 | K19+034.496 | K19+154.496 | Concave | 8000 | 140 | K             |
| 16          | K19+752.131  | K19+872.131 | K19+951.757 | K20+031.384 | K20+151.384 | Concave | 3000 | 52.5 | M             |

### 3. Method

#### 3.1. Design and scenario

In order to compare the difference between on-ground and underground roads, two roads with exactly the same linear shape were constructed in the study. One is a typical urban road traffic environment and the other is an underground road environment; both adopt a representative three-lane road cross section and 3.5m lane width, the hard shoulder on the left and right sides is 0.5m; the curved road section does not consider the widening design, and no cross slope is set. The underground road adopts a cross-sectional structure with an overhaul road of 1.00m and a clear height of 6.5m, While the on-ground road adopts a sunny day with normal light environment. At the same time, in order to reduce the interference of irrelevant factors, the experimental road traffic flow is set as free flow.

The experimental design adopted in this study is a 16×2×2×2 in-group experimental design, in which the road environment is an independent variable, including two conditions: on-ground road and underground road; curve direction and driving lane (only the inner lane and Outer lane) are considered as two dependent variables, and different linear combinations are considered as another dependent variable, including 16 conditions. The research dependent variables are driving speed and lane deviation.

![Figure 2 Environment of the on-ground and underground simulation road for experiment](image-url)

#### 3.2. Participants

As individual driver differences have little effect on the results of in-group experimental. Participants selecting only considered the balance of novice and skilled, young and elderly, and male and female. Finally 15 drivers subjects took part in the experiment, including 14 males and 1 female; whose age was 28-51 years old, with an average of 36.7±8.11 years old; driving experience was 1 to 32 years, with an average of 11.7±8.60 years.

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3.3. Equipment
The research uses an eight-degree-of-freedom research-type traffic safety driving simulator built by the Research Institute of Highway Ministry of Transport. The system is integrated and built by Japan Forum8 and Korea INNO simulator Ltd.. It is composed of a motion platform, a sphere simulation cabin, projection system, Sound system, vehicle simulation system, scene generation system, control platform, power supply system, related auxiliary system and data recording system. The motion platform is provided by Bosch Rexroth, which is composed of a six-degree-of-freedom motion platform (6DOF), a long-stroke unit (X-Table), a system turntable (Yaw-Table) and a vibration table (Vibration). The motion system provides the driver with a real driving experience; the simulation cabin uses a closed sphere with a diameter of about 4m and a height of about 3.5m, with a built-in simulation vehicle, and provides the replacement function of large and small vehicles (accord real vehicles and simple trucks). Above the cockpit 8 Belgian Barco customized Sim5W professional projectors were equipped, providing up and down 40° Level 360° Panoramic projection; the vehicle simulation system can simulate the performance of various vehicles through professional vehicle performance simulation software CarSim and TruckSim. The scene generation and control system is developed on the basis of Uc-winRoad software from Forum8, which can be real in the 3D earth according to the design file, and simulate the road environment in various situations through weather, temperature, road friction, slope treatment, traffic flow settings, and related textures and model modifications. The data recording system can record nearly a hundred items of data such as clutch, vehicle speed, acceleration, lane position, in real time. Also data collected by cardiac physiological devices such as FaceLab eye tracker can be synchronized for analysis by researchers.

Figure 3 Driving simulator used for research

3.4. Process
Subjects were informed of the discomfort may be bring by the simulator and were demanded to sign the experiment participation consent form first.
Before the formal experiment, subjects were familiar with the operation and feeling of the simulator by loading a non-test road. After they were proficient in the operation of the simulator, the formal experiment would started. Each driver will randomly carry out six test tasks of road round trips and three lanes. Each trial took about 20 minutes. For each 40-minute test, the subjects will be asked to rest for 10 minutes.

3.5. Data recording and analysis
The simulator can record and output the driving behavior data of each test subject, process the data through EXCEL and R, generate secondary data for the experiment, then analysed by SPSS19.0. With the help of EXCEL and other software to complete the chart production.

4. Results and discussion
4.1. Differences between on-ground and underground roads
Based on the descriptive statistics and variance analysis of the on-ground and underground road speeds and lane offsets on the left and right lanes of each test section, the results of the differences in driving behavior on-ground and underground roads are as follows:
(1) There is no obviously difference between the driving speed of the underground and on-ground road; most driving speed changes of the test sections are basically same. But speed of the right lane on section 9 and section 16, left lane of section 5 and section 13, both lane of section 8, are not consistent.

(2) Lane offset changes between the underground and on-ground road are also basically same, except the right lane of test section 0 and left lane of test section 6. But the difference of the observation points were significant: for the underground road left lane, lane deviation of some sections is smaller than the on-ground road; while for the right lane, they were larger.

4.2. Differences between lanes
Descriptive statistics and T test analysis of the left and right lanes of each test section shows that:

(1) Although there are significant speed differences between the left and right lanes at some observation points of the on-ground or underground roads, but the overall speed difference between lanes can be ignored.

(2) The difference of lane offset between the left and right lanes of the on-ground and underground roads in each test section is generally significant, and the lane offset of the left lane is smaller than that of the right lane. This is mainly because the driver is accustomed to being close to left in the current lane and to the center of the road when there are multiple lanes. At the same time, the difference between the lane offsets of the left and right lanes of the underground road is more obvious than that of the on-ground road, which indicates that the driver is more inclined to drive closer to the center of the road when driving on the underground road.

4.3. Differences between two test sections of the same combination type
Through descriptive statistics and variance analysis of driving behavior data of two test road sections involving 8 types of horizontal and vertical linear combinations, the overall conclusion of the comparison results of the main observation points of the two test sections of each combination type shows that:

(1) The horizontal curve line shape affects the driver's lane deviation more. For the same linear combination, if the two test sections have different horizontal curve directions, the driver's lane deviation difference in the horizontal curve section will increase.

(2) The vertical curve shape affects the speed of the drivers’. The speed of the driver on the uphill and downhill sections is generally stable, while it increase significantly after the uphill, and decrease steadily after the downhill. For the same linear combination, if the vertical curves of the two test sections are opposite, the speed difference between the driver before or after the change point will gradually increase.

4.4. Comparison between different combination types
(1) Test section 0 is a long straight line, which is a downhill first, then flat slope. Results shows that except points B (900m before the point of change) and point C (600m before the point of change) on the outer lane slope of the on-ground road, the speed and lane offset between adjacent observation points of the inner lane of the on-ground road, and the inner and outer lanes of the underground road change small. Which shows that the longitudinal slope on the underground road has less impact on the driver than the on-ground road. Compared with the increase of the driver's downhill speed caused by the existence of the on-ground road longitudinal slope, we do not have to worry about this problem of the underground road.

(2) Combination A is a line that horizontal curve is on the up and down slope, and the starting point of the horizontal curve coincides with the variable slope point. For Test section 1 which is turning left with uphill. The lane offset from the middle point of the second easement curve to the end of the second easement curve of the outer lane of the on-ground road has a large change; the difference of speed and lane offset between the adjacent observation points of the inner lane of the on-ground road and the inner and outer lanes of the underground road is not significant. For Test section 9 which is turning right with downhill. For the inner lane of the on-ground road and the outer lane of the
underground road, the lane offset from the middle point of the second easement curve to the end of the second easement curve varies greatly; While for the outer lane of the on-ground road and the inner lane of the underground road, the speed and lane offset between the adjacent observation points has no obviously difference. The result shows that for the on-ground road adopts combination A, if it is an uphill with left turn, we should consider taking certain safety measures to prevent vehicles in the outer lane from deviating too much to impact vehicles in the middle lane from the middle point of the second gentle curve of the horizontal curve to the end of the second gentle curve; if it is a downhill with right turn, relevant safety measures should be considered to avoid the drastic changes in the lane deviation of the inner lane vehicle from affecting vehicles in other lanes. For the underground road adopts combination A, if it is downhill with right turn, certain safety measures should be taken to avoid vehicles in the outer lane deviating too much to impact vehicles in the middle lane from the middle point of the second gentle curve of the horizontal curve to the end of the second gentle curve.

(3) Combination C is a line that the end point of the first transition curve of the horizontal curve coincides with the variable slope point, the first transition curve of the flat curve is located on the up and down slope, and the circular curve and the second transition curve are located on the flat slope section. For test section 2 which is turning right with uphill. Section from the midpoint of the first transition curve to the end point/gradient point of the curve, and section from midpoint of the second transition curve to the end of the second transition curve, lane offset of inner lane have obviously difference; while section from midpoint of the second transition curve to the end of the second transition curve, lane offset of outer lane have obviously difference, on both On-ground and underground road. For test section 10 which is turning right with downhill. Section from the midpoint to the endpoint/gradient point of the first transition curve, Section from the midpoint to the endpoint/gradient point of the second transition curve, lane offset in the inner lane of on-ground road changed much. Results shows that for both on-ground and underground roads adopts combination C, if it is uphill with turning right, we should consider safety of inner lane from the midpoint to the end point/variable slope point of the first transition curve, and from the midpoint to the endpoint of the second transition curve. Certain measures should also be taken to prevent lane offset of vehicles in the outer lane change too much from the midpoint to the endpoint of the second transition curve. If it is downhill with turning right, for on-ground road, safety should be considered from the midpoint to the end point/gradient point of both the first and second transition curve.

(4) Combination E is a line that the starting point of the horizontal curve is on the flat slope, and the midpoint of the first transition curve to the end of the horizontal curve is on the up and down slope. Both test section 3 which is downhill with turning left and test section 11 which is uphill with turning right, for the inner lane and outer lane of on-ground road, outer lane of underground road, lane offset changed much from the midpoint to the end point of the second transition curve. Which means that when adopting combination E, certain measures should be taken to avoid large lane offset of vehicles from the midpoint to the endpoint of the second transition curve on-ground road, whether it is a downhill with turning left or uphill with turning right. For underground road, lane offset of outer lane should be considered from the midpoint to the endpoint of the second transition curve.

(5) Combination F is a line that the first transition curve of the flat curve is on the up and down slope, and the circular curve and the second transition curve are on the flat slope. For test section 4 which is downhill with turning right, lane offset of inner lane of on-ground road changed much from the midpoint to the endpoint of the second transition curve, while both lane offset and speed changed little on underground road. For test section 12 which is uphill with turning right, lane offset of inner lane of both on-ground and underground roads changed much from the midpoint to the endpoint of the second transition curve, while lane offset of inner lane of on-ground road also changed much from the midpoint to the endpoint/slope point of the first transition curve, and from the startpoint to the midpoint of the second transition curve. The results means that if the on-ground road design adopts combination F, Whether it is a right turn downhill or a right turn uphill, safety measures should be taken from the midpoint of the to the endpoint of the second transition curve. when it is uphill with turning right, measures should also be taken in the inner lane from the midpoint of the first transition
curve to the starting point/gradient point of the circular curve, and from the starting point to the midpoint of the second transition curve. When the underground road line design adopts combination F, and it is an uphill with turning right, safety measures should also be considered to prevent the vehicle from deviating too much from the midpoint to the endpoint of the second transition curve.

(6) Combination G is a line that the midpoint of the circular curve coincides with the variable slope point, the first half of the horizontal curve is on the flat slope, and the second half is on the up and down slope. For test section 5 which is uphill with turning left, there is significant lane offset changes from the startpoint of the first transition curve to the vertical curve in the outer lane of the on-ground road. For test section 13 which is downhill with turning left: there is no speed and lane offset significant difference between the observation points in any lane both on-ground and underground roads. Means that if the linear design adopts the combination G, and it is an uphill with turning left, relevant safety measures should be taken to avoid the deviation of the outer lane vehicles from the starting point of the first transition curve to the starting point of the vertical curve.

(7) Combination H is a line that the midpoint of the circular curve coincides with the variable slope point, the first half of the horizontal curve is on the up and down slope, and the second half is on the flat slope. For test section 6 which is uphill with turning left, lane offset of both lanes on-ground road change much from the midpoint to the endpoint of the second transition curve. For test section 14 which is downhill with turning right, lane offset of inner lane on-ground road change much from the midpoint to the endpoint of the second transition curve. Which means that if the combination H is adopted in the alignment design of the road on-ground, if it is uphill and turning left, safety measures should be taken to prevent vehicles from deviating too much from the midpoint to the endpoint of the second transition curve. And if it is downhill with turning right, measures should also be taken to avoid large changes in lane deviation of vehicles in the inner lane from the midpoint to the endpoint of the second transition curve.

(8) Combination K is a line that the starting point of the second transition curve of the flat curve coincides with the variable slope point, the second transition curve of the flat curve is located on the up and down slope, and the circular curve are located on the flat slope. For both test sections (section 7 which is downhill with turning left and section 15 which is uphill with turning left), there is no speed and lane offset significant difference between different lanes of the on-ground and underground road. Lane offset changed much from the midpoint of the circular curve to the start point of the second transition curve/gradient point of the circular curve, midpoint to the endpoint of the second transition curve in section 7 outer lane. While lane offset also changed much from midpoint to the endpoint of the second transition curve in section 15 outer lane. The results means that if on-ground road alignment design adopts combination K, and it is downhill with turning left, safety measures should be considered for the outer lane from the midpoint of the circular curve to the start point of the second transition curve/gradient point of the circular curve, and from midpoint to the endpoint of the second transition curve. And if it is uphill with turning left, safety measures should be taken to avoid vehicles in the outer lanes swing from midpoint to the endpoint of the second transition curve.

(9) Combination M is a line that end-point of the second transition curve coincides with the variable slope point, and the horizontal curve is on the up and down slope. For section 8 which line is turning left on downhill, drivers has a large change in lane offset from the vertical curve start point to horizontal curve second easement curve end point/variable slope point in the outer lane whether on-ground road or underground road, while there is no speed or lane offset difference in the inner lane of section 8 and both lanes of section 16. Results shows that if road design adopts combination M, if it is downhill and turning left, certain safety measures should be considered to avoid vehicles in the outer lane from the starting point of the vertical curve to the end point of the second gentle curve/change point of the horizontal curve.
Figure 4 Comparison of driver lane offsets in different lanes of on-ground and underground roads with different linear combinations

Legend: The red solid line in the figure indicates the horizontal curve line, the upward convex means a right turn, and the concave downward means the left turn; the blue solid line indicates the vertical curve line, indicating flat slope, uphill, downhill and variable slope points respectively; black dotted line Mark the three selected observation points before and after the linear combination; the red dashed line indicates the main observation point of the horizontal curve; the blue dashed line indicates the start and end points of the vertical curve; the green dashed line indicates the slope point (mostly coincides with a main observation point of the horizontal curve); The red and green arrows and the direction respectively indicate the significant increase and decrease of the lane offset (to the left of the current traffic lane).

5. Conclusions and prospects
Based on the driving simulation experiment of eight types of horizontal and vertical combinations and 16 test sections on-ground and underground roads, this study explored the differences in driving behaviors of different linear combination schemes on-ground and underground roads, and tried to analyze the applicability of each linear combination scheme on the underground by the driving behavior difference. The results shows:

   Based on the driving simulation experiment of eight types of horizontal and vertical combinations and 16 test sections on ground and underground roads, this study explored the differences in driving behaviors of different linear combination schemes on ground and underground roads, and tried to analyze the driving behavior of each linear combination scheme in the underground. The study found:

   (1) There is little difference in the driving speed of drivers on ground and underground roads; the difference in lane deviation is significant. Due to the side wall of the underground road, the deviation of the left lane (to the left) is less than that of the above ground road, and the right lane (toward the road) (Left) The lane offset is greater than that of the above-ground road; however, the driver's operation rules on the test sections of the above-ground and underground roads are basically the same.
(2) Regardless of whether it is an over-ground road or an underground road, the driving speed difference between the left and right lanes is not large; the lane deviation is all the left lane is smaller than the right lane; at the same time, due to the side wall of the underground road, the left and right lanes are offset. The difference is smaller than the road on the ground.

(3) The horizontal curve line shape affects the driver's lane deviation more. For the same linear combination scheme, if the two test road sections have different horizontal curve directions, the driver's lane deviation difference in the horizontal curve section will increase. The vertical curve shape affects the driving speed of the driver. The speed of the driver in the uphill and downhill section is generally stable, but the speed of the driver will increase significantly after the uphill end, and the speed will decrease steadily after the downhill end. In the same linear combination scheme, if the vertical curves of the two test sections are in opposite directions, the speed difference between the driver before or after the change point will gradually increase.

(4) The dangerous points in bad linear combination schemes are mostly located from the midpoint of the second easement curve to its end point (HZ point). For individual combinations, the midpoint of the first easement curve to the starting point (HY point) of the circular curve is also a sudden change in driving behavior. Point.

(5) There are more types of linear combination schemes applicable to underground roads than above-ground roads. The best combination types include combination type 7, combination type 8 and combination type 11; combination type 1, combination type 5 and combination type 6 are required when used Consider the safety issues from the midpoint of the second transition curve to the HZ point; when using combination type 3, consider the safety issues from the midpoint of the first transition curve to the HY point/sloping point at the same time; when using combination type 13, consider the vertical safety issues from the starting point of the curve to the variable slope point/HZ point.

Since the design of a long experimental section will bring fatigue to the driver’s simulated driving, which will affect the validity of the experimental data, this study considers the experimental time and based on the designer’s suggestion. Only eight linear combinations are selected and targeted, two test sections were selected and designed for each linear combination plan. Although a more reliable conclusion was obtained from the research results, because there are not all linear combination plans and the possible horizontal and vertical combination types of various combination plans, there is no need for each combination type. The conclusions on the difference between horizontal and vertical lines are not rich enough. As the linear combination design is the core of road design, it is necessary to carry out more research to improve the results of this research. At the same time, driving simulation is an effective traffic safety research method. It is very effective and widely recognized to carry out comparative analysis studies similar to those discussed in this research. However, its absolute effectiveness has also attracted much attention. The driver's driving speed and lane offset values obtained under various working conditions must be verified by relevant physical engineering before they can be used directly.

Acknowledgments
This work was supported by the project “Research on key technologies for the construction and operation of underground interchanges in mountainous expressways (SY-2019-XLGS-004-200)”.

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