A VEHICLE-TERRAIN ANALYSIS ON THE MAXIMUM DESIRABLE GRADES FOR THE RESIDENTIAL DRIVEWAY PROFILES

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ABSTRACT

Driveways, serving as the junction points between public roadway and private sites, play an important role in the safety and operational performance of roadways. The geometric design of the residential driveways, comprising of the horizontal alignment, vertical profile, and cross sections must accommodate the selected design vehicles in order to avoid any vehicle-terrain conflicts. These conflicts may lead to vehicle or infrastructure damages or unnecessary speed reductions affecting safety and capacity. Traditionally, the horizontal design (e.g. curb return radii and turning lane widths) can be checked by performing a vehicle swept path simulation or superimposing a two-dimensional (2D) turning template. The design would be adjusted to suit the vehicle's turning characteristics and swept path clearance envelopes. As to the vertical design, design guidelines, such as the Geometric Design Guide for Canadian Roads (GDGCR) from the Transport Association of Canada (TAC), indicate maximum slopes and recommended profile designs. Although the ground clearances of design vehicles are not provided in the publication, it is assumed the recommended slopes have taken those values into consideration. With current technology, the driveway design can be easily modelled in three-dimension (3D) within a CAD environment, and 3D vehicle swept path analysis can be performed to determine if parts of the vehicle will come into contact with the ground. In this study, the authors analyzed the maximum recommended driveway profiles (i.e. uphill and downhill) from the GDGCR to reverse engineer the minimum allowable ground clearances for three of the TAC design vehicles (i.e. P, B12, LSU), two of the Low Clearance Vehicle (i.e. fire truck, and garbage truck) from the NCHRP Report 659 and an ambulance. Next, applying the calculated minimum allowable ground clearances for the selected vehicles, the authors performed 3D vehicle swept path simulations on the 3D surface of the driveway in CAD. Results from 3D driveway analysis highlighted vehicle-terrain conflicts that were not exposed in the 2D driveway profile analysis.

LITERATURE REVIEW

The driveway is recognized by GDGCR (1) as an important element for the performance of the road systems. The design is influenced by multiple factors that vary depending on the driveway's location and the corresponding land use (e.g. residential, commercial, industrial). Guidelines typically recommend horizontal and vertical design geometry to accommodate the design vehicles' turning paths and ground clearances. In the GDGCR (1), the maximum uphill and downhill profile grades for the residential driveways were recommended. Depending on the region, supplements published by municipalities (13) will provide additional guidance on specific values for grades based on local conditions.

Although the guideline provides both the vertical and horizontal design geometry for driveways, the GDGCR (1) doesn't provide values on the ground clearances for the design vehicles. For local roads, the guideline recommends the designers to use their own discretion on the grades based on the selected design vehicle. For any vehicle, these variables, including front and rear overhang lengths, the wheelbase length, and their correspondent clearances (i.e. front overhang, rear overhangs and wheelbase ground clearances) could influence the grades. Figure 1 depicts these variables on a passenger car. Furthermore, the maximum desirable grades are influenced by the specific overhangs (e.g. the maximum desirable grades when the vehicle is going uphill will be influenced by the vehicle's front or rear overhang clearances, the maximum desirable grades when the vehicle is going downhill will be influenced by the vehicle's wheelbase clearances).

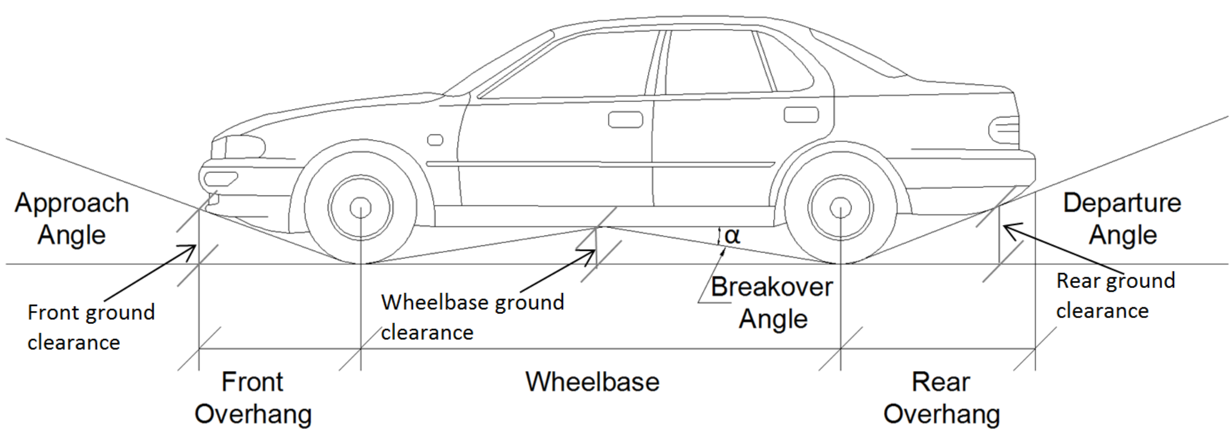

Figure 1. Vehicle profile example and key components for the 2D estimation of the design grades

These ground clearances, do not account for any dynamic effects that the vehicles may experience as a consequence of braking or suspension compression; they are only based on the evaluation of the vehicle's profile geometry and ground clearances for the recommended maximum desirable grades.

In the United States, many studies have been conducted (2-9) to analyze driveway geometry for improving the adjacent roadway performance. In one study, the NCHRP Report 659 (10) captures a series of Low Clearance Vehicles (LCVs). Although they are not catalogued as design vehicles in GDGCR, these vehicles, such as garbage trucks, fire trucks, and ambulances should still be considered in the design as they would need to access the driveway for operational reasons. Alleviating issues between design geometry and design vehicles are crucial for reducing the impact on the overall performance of the driveway. Similar to driveways, rail crossing designs need to accommodate LCV (6-12).

Some of these LCVs (10), have been suggested for driveway design; as they may need to have access through them to different areas like industrial or residential areas due to operational reasons.

The studies overall, suggest changes to the existing guidelines in regards to different aspects including the recommended vertical geometry, e.g. maximum recommended grades for the different types of driveways, the minimum separation distance based on capacity and adjacent roads, etc.

METHODOLOGY

This study is separated into two parts. The first part involves 2D analysis while the second part involves 3D analysis. To perform the analysis, tools including Autodesk AutoCAD (17), NEXUS Intersection® (15) and AutoTURN PRO 3D® (16) were used to serve as the CAD platform, intersection modelling tool, and 3D vehicle simulation tool respectively.

The objective of the first part is to determine the ground clearances of the selected design vehicles including the passenger car (P), light single unit truck (LSU), standard bus (B-12), rear-load garbage truck, aerial fire truck, and ambulance (B-AUTO) using a simplified approach. The first three vehicles originated from the GDGCR (1) publication and the last three vehicles are LCVs originated from the NCHRP Report 659 (10) and the Crow guidelines. Figure 2 depicts the vehicles and their dimensions.

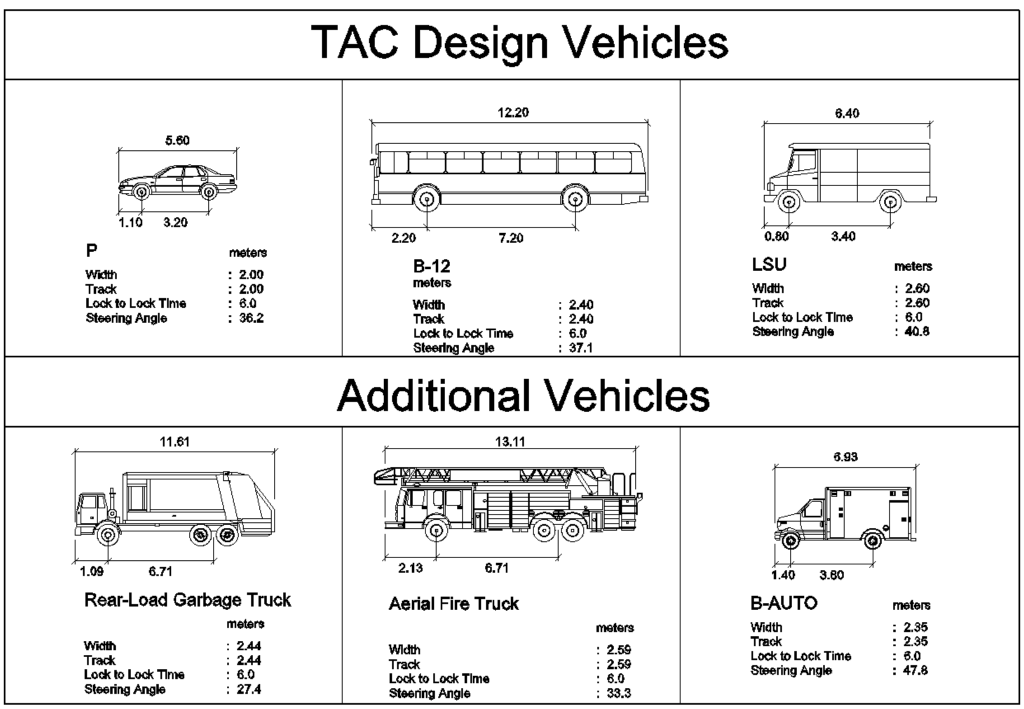

Figure 2. Vehicles selected for the evaluation of the residential driveway model.

In order to perform the analysis, the 2D driveway profiles with the maximum desirable grades recommended by GDGCR were produced in CAD for two different scenarios: uphill and downhill driveways. The vehicle simulation tool was used to perform the vehicle-terrain analysis. By varying the ground clearances for each vehicle and evaluating the driveway profiles, the Minimum Ground

Clearance (MGC) values for each vehicle were determined through trial and error. These MCG values represent the thresholds for each vehicle. In other words, if the vehicle uses the calculated minimum ground clearances, they would not encounter any issues on the driveway profiles.
Special attention is recommended when establishing the maximum grades for emergency vehicles such as ambulances and fire trucks, whose service times are crucial for the type of service they provide. Limited access for these vehicles can result in expensive property and/or vehicle damage, as well as life-threat risks if the driveway is inaccessible.

The objective of the second part is to take the calculated MGCs for the vehicles and perform the analysis in a 3D environment. First, the driveway geometry is created in 3D based on the same vertical profile information. With an assumption of 2% crown at the one lane entry and exit driveway, 3D surfaces in CAD was created to represent the downhill and uphill scenarios. Using the vehicle simulation tool and the calculated MCG from part one, a more realistic analysis including of a right and left turn into the driveway was performed. When conflicts between the vehicle and surface were observed, the results were recorded.

FINDINGS

Section 1

In the first part of the study, the two driveway scenarios representing the boundary conditions for the residential driveway as per the GDGCR recommendations were modelled in CAD. Figure 3 depicts the profile for the recommended grades going uphill and downhill.

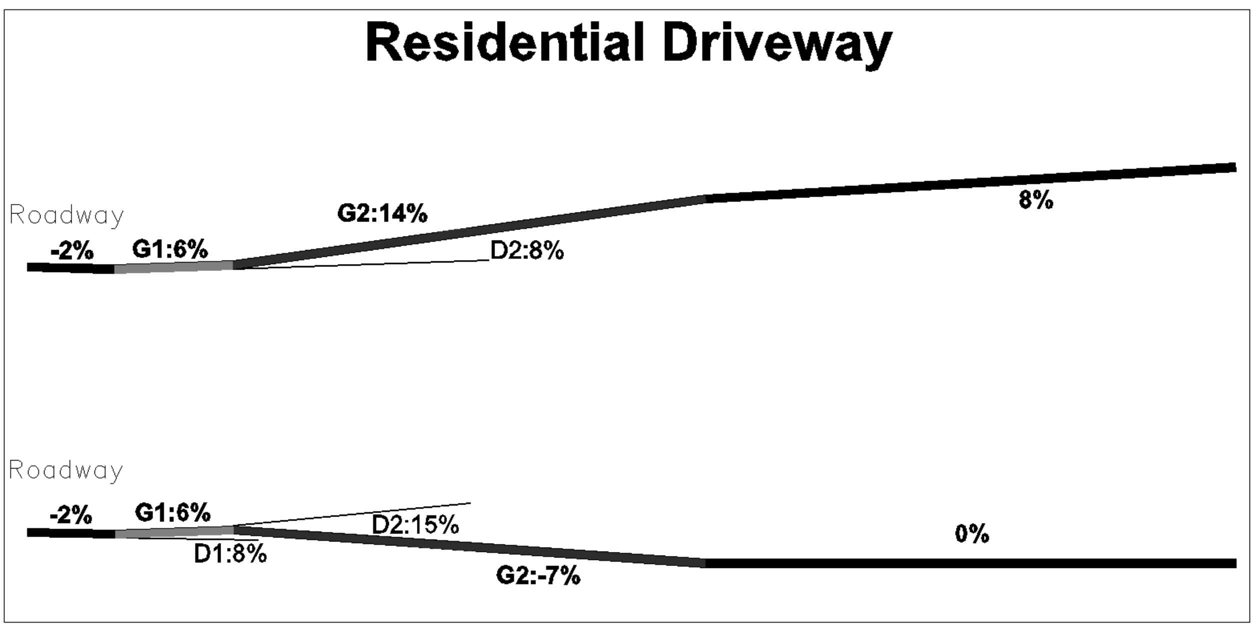

Figure 3. Uphill and downhill profiles based on thresholds grades recommended by GDGCR.

For the vehicles, the lengths of the vehicle's overhangs and wheelbase were kept constant and the ground clearances were varied until no conflicts were observed. Through a trial and error process of simulating the vehicle iteratively with a 1 cm incremental ground clearance height at each of the front overhang, wheelbase, and rear overhang, the maximum thresholds can be determined. Figure 4 shows a sample of the analysis. The top two simulations, created using the light single unit truck, illustrate the uphill profile while the bottom two simulations illustrate the downhill profile. The second and forth simulations (from the top) showcased when the clearance values produced conflicts while the first and third simulations (from the top) showcased the thresholds of values in which no conflict was observed.

Upon testing the six different vehicles, it was observed that the front overhang ground clearance ranges from 0.06m to 0.24m, the wheelbase ground clearance ranges from 0.09m to 0.21m, and the rear overhang ground clearance ranges from 0.08m to 0.42m. In addition, it was noticed that the B-12 bus required the highest wheelbase ground clearance height due to its wheelbase length. Both the B-12 bus and fire truck had the highest front overhang ground clearance height at 0.24m. The fire truck required the highest rear overhang ground clearance height at 0.41m.

Furthermore, the LSU truck shown in Figure 4 is a good example of how the relationship between overhang length and the scenario affects the calculated ground clearances. In this case, the short front overhang length allows the vehicle to overcome the grades going uphill easily, even if the vehicle had low ground clearance. On the other hand, the long rear overhang of this vehicle scrapes the terrain even though the ground clearance for this component is a lot higher than the front clearance. A similar behavior can be observed for the NCHRP garbage truck and the fire truck.

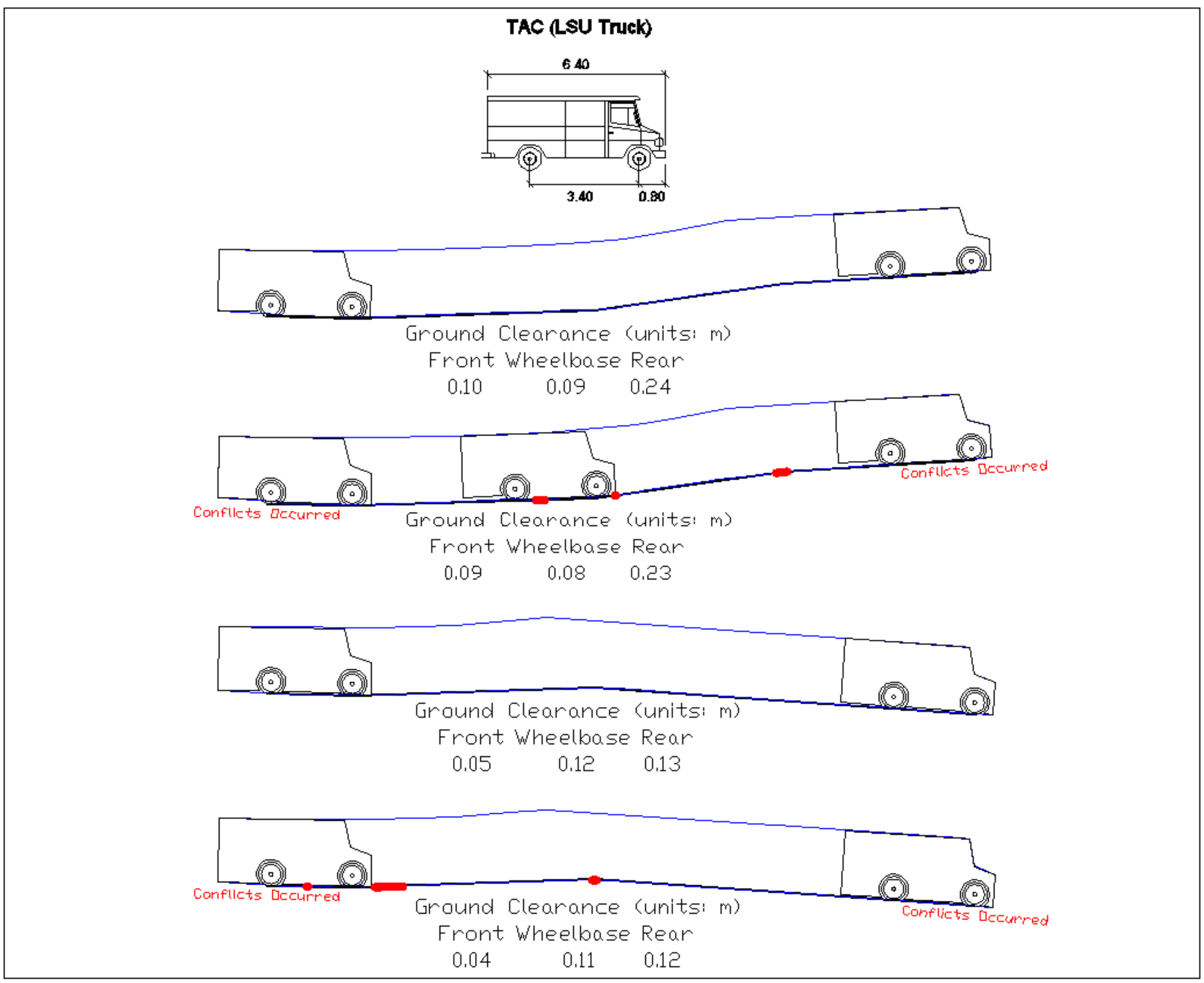

Figure 4. Sample of vehicle ground clearances analysis of light single unit truck.

Table 1 presents the results for the minimum ground clearance thresholds identified for the vehicles based on the minimum desirable grades from the GDGCR.

Table 1 Minimum vehicle ground clearances for driveway vertical geometry evaluation in 2D.

Vehicle	Driveway Vertical scenario geometry	Min. Front clearance for vertical geometry (m)	Min. WB clearance for vertical geometry (m)	Min. rear clearance for vertical geometry (m)
P-car	Uphill model	0.13	0.09	0.14
	Downhill model	0.07	0.11	0.08
B12 Bus	Uphill model	0.24	0.18	0.31
	Downhill model	0.12	0.21	0.16
LSU Truck	Uphill model	0.10	0.09	0.24
	Downhill model	0.06	0.13	0.16
NCHRP 659 garbage truck	Uphill model	0.13	0.16	0.38
	Downhill model	0.07	0.21	0.19
NCHRP 659 Fire truck	Uphill model	0.24	0.17	0.42
	Downhill model	0.10	0.20	0.20
Ambulance	Uphill model	0.15	0.10	0.20
	Downhill model	0.08	0.13	0.10

Section 2

For the second part of the study, the driveway was modelled in 3D by combining horizontal and vertical geometry. To simplify the creation of the 3D scenarios, NEXUS™ Intersection was used to create the driveway surface. Afterwards, the 3D turning simulation software, AutoTURN PRO 3D®, was used to produce the simulation and conflict analysis. An example of the driveway surface model and a right turn simulation in 3D for the fire truck is shown in Figure 5.

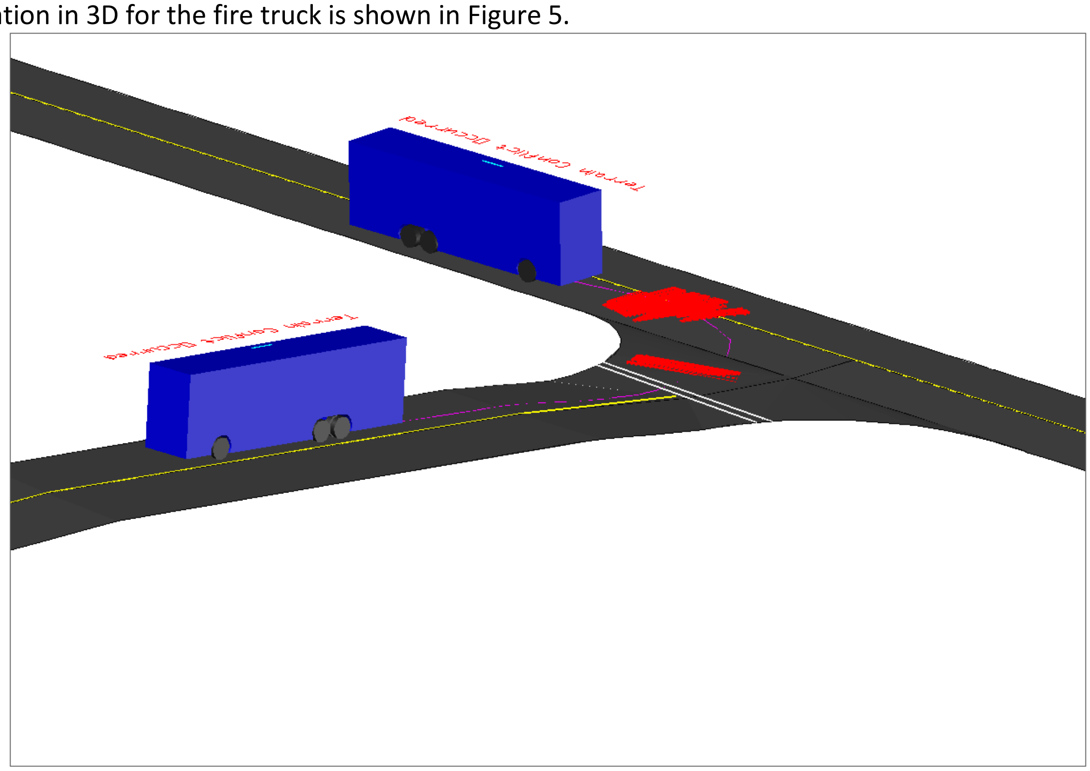

Figure 5. 3D driveway modeling and right turn simulation for the NCHRP 659 fire truck.

The interaction between the vehicle tires and the surface as the vehicle executes the turn can be observed. When the underside of the vehicle scrapes the ground, the area is highlighted in red as shown in Figure 5. Also, since the interaction between the wheels and the surface varies depending on the type of turn, left and right turn maneuvers were recreated and analyzed for all the vehicles. The minimum clearances identified in Section 1 were used for the 3D vehicle simulations. Figure 6 illustrates the downhill scenario evaluated in 2D versus 3D. It can be observed that the 2D analysis (top) assumes the vehicle is travelling straight across the recommended grades. Whereas, in the 3D scenario, the vehicle makes the left or right turn into the driveway and the centerline path of the vehicle will experience different grades until the vehicle has straighten out.

From the results, it showed that even though the calculated maximum ground clearances from Section 1 did not produce conflicts in the 2D analysis, the vehicles with the same values would encounter conflicts with the surfaces. This is due to the interaction between the vehicle and the driveway's surface. For the 2D analysis, the vehicle tires on the same axle are assumed to be traveling at the same grade; in the 3D model, the front left tire can be traveling on a different grade than the front right tire.

The 3D model also showed the severity of the conflicts, evidencing how the vehicle part scrapping the surface changed with the type of turn (i.e. left turn or right turn).The driveway scenario (i.e. uphill or downhill), evaluation also indicated that conflicts were more pronounced in the case of the downhill left turn scenario. Figures 6 and 7 depict the results for the light single unit truck. In the case of the 3D simulations, Figure 6 shows the downhill driveway scenario whereas Figure 7 shows the uphill scenario. For left and right turns, when using the MGCs from the analysis in Section 1; it is clear how, while these worked fine for the vertical geometry, the 3D scenario using the same geometry as reference highlighted issues.

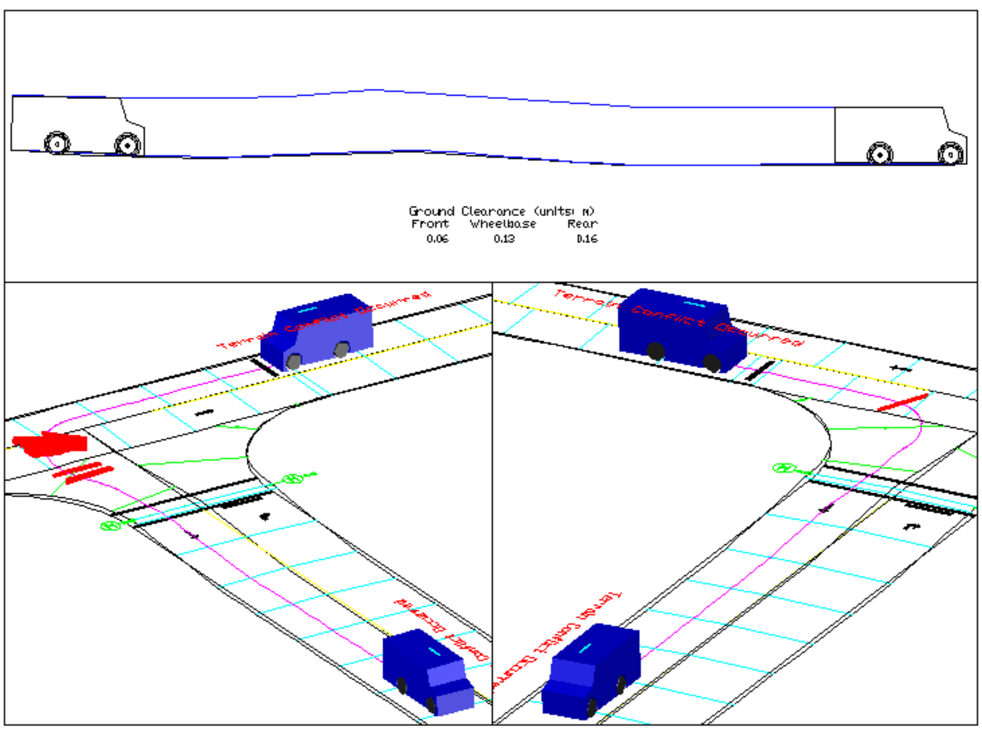

Figure 6. Results for 2D and 3D simulation using the Light Single Unit Truck on the downhill model.

In the case of the downhill scenarios, the left turns highlighted more conflicts between vehicles and terrain than right turns. As the vehicle crosses the roadway crest and given the roadway width, the length between the roadway's crest and grade change may result too short for certain vehicles.

In the uphill scenario, the 3D simulation did not highlight any issues with the driveway's surface for the left turn; although a conflict was identified for the right turn, particularly where the vehicle is transitioning from the desired maximum grade 1 to the desired maximum grade 2.

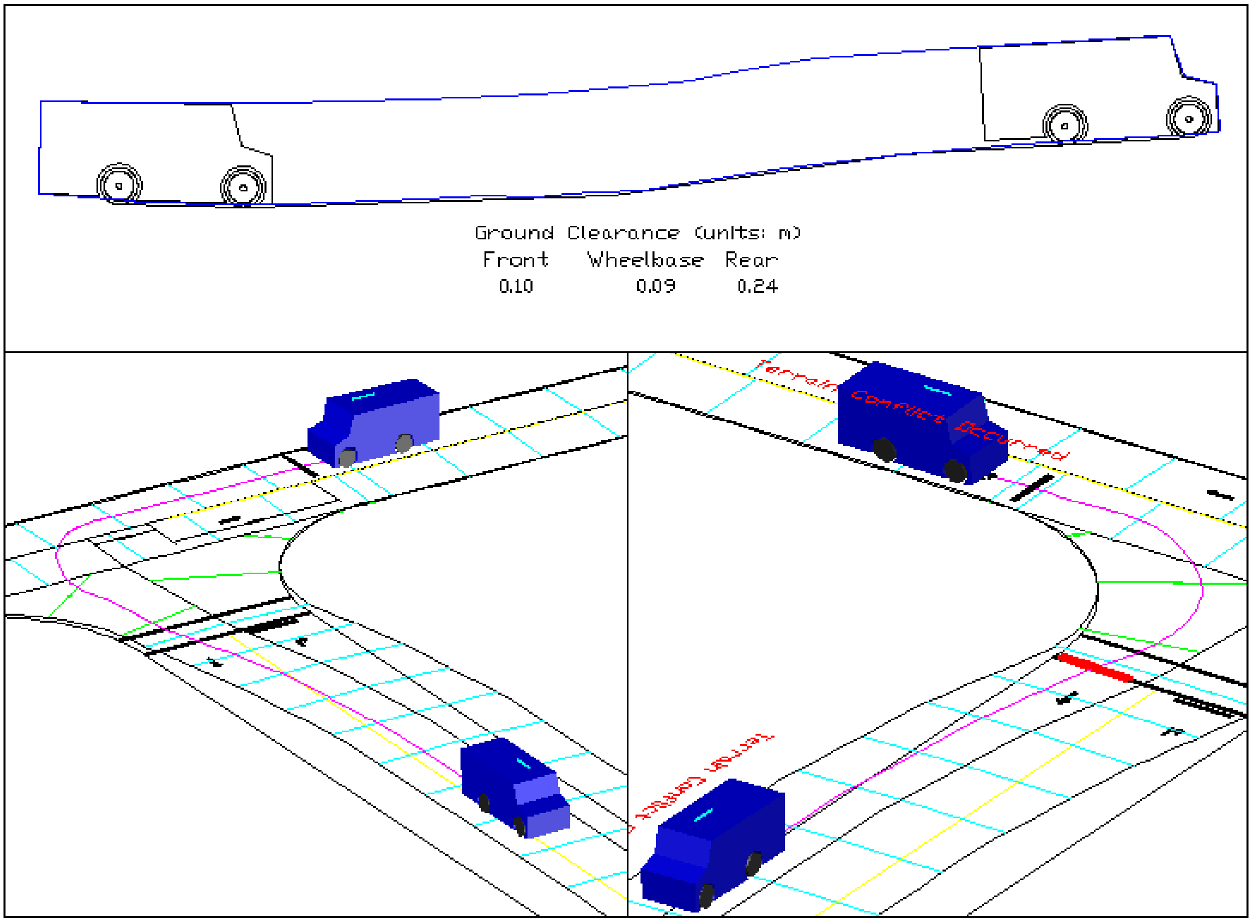

Figure 7. Results for 2D and 3D simulation using the Light Single Unit Truck on the uphill model.

In the case of the simulations for the NCHRP vehicles, both the driveway vertical geometry and 3D model highlighted issues. Since the ground clearances and overhangs of these two vehicles are taken into account for several technical documents and their characteristics are based on comprehensive studies, it would be highly recommended to conduct similar studies in order to incorporate similar vehicles in the Canadian design guidelines.

Figure 8 illustrates the 3D simulation results for various vehicles while performing left and right turns for the uphill and downhill scenarios. The vehicles correspond to the passenger car and B-12 bus from the TAC design guideline and the garbage truck from the NCHRP report 659. The top six simulations present the results for downhill driveway scenario and the lower six simulation present the findings for the uphill driveway scenario. The differences in regards to the severity of the conflicts between each scenario and type of turn can be observed.

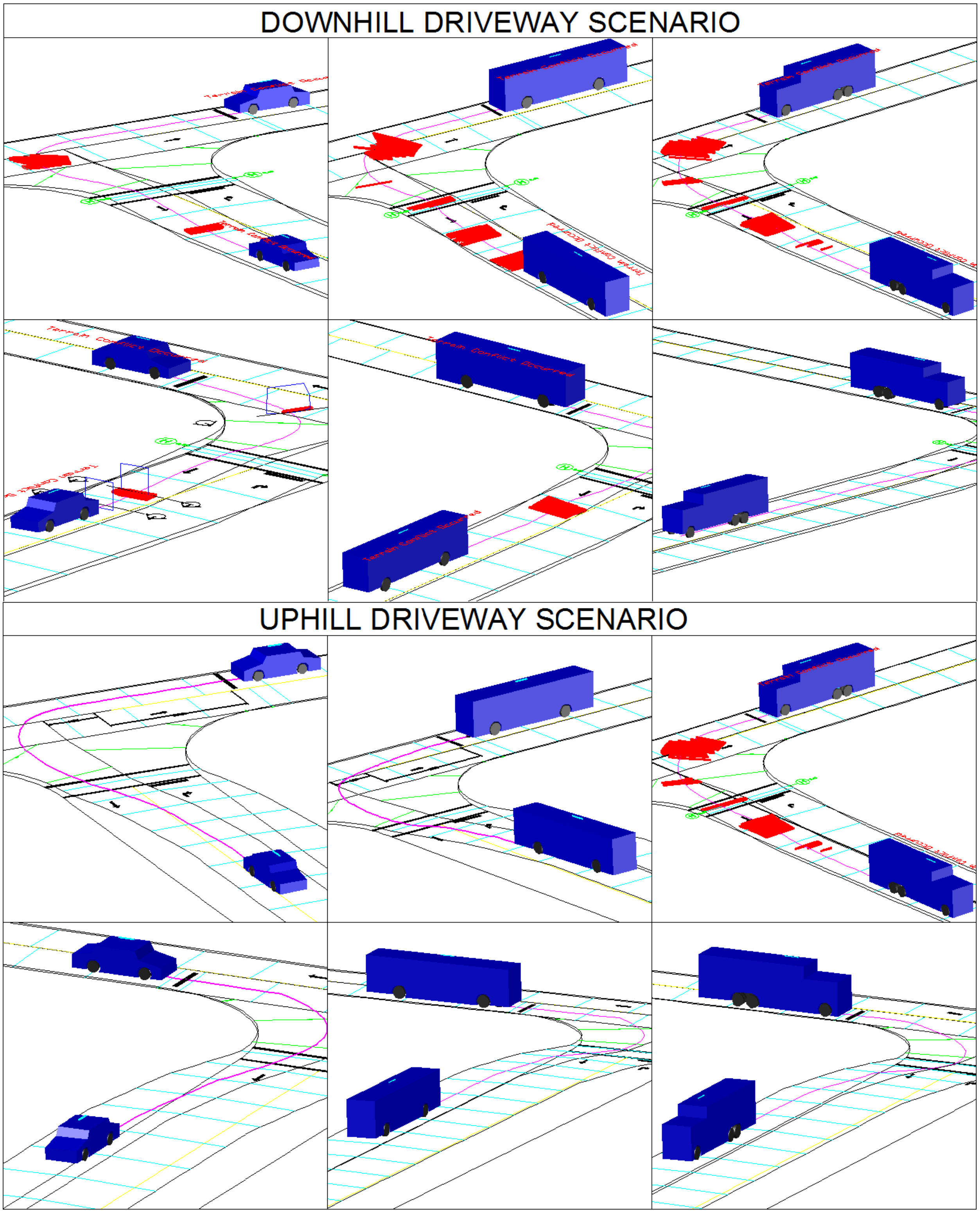

Figure 8. Simulation results for the uphill and downhill driveway scenarios.

Finally, Table 2 presents the results of the 3D analysis and simulations for all the vehicles using the ground clearances described in Table 1. In the table, the dots in red indicate that the 3D simulation highlighted a conflict between the surface and the vehicle component (i.e. front overhang, wheelbase or rear overhang) as the vehicle executed the turn. Therefore, a red dot indicates that the minimum ground clearance identified in Section 1 from the 2D analysis is not sufficient for the vehicle to successfully navigate the driveway.

Table 2. Minimum driveway evaluation for Driveway 3D simulation results.

Vehicle	Vehicle Part	Uphill driveway		Downhill Driveway	
		Right Turn	Left Turn	Right Turn	Left Turn
P-car	Front	-	-	●	●
	Wheelbase	-	-	●	●
	Rear	-	-	●	●
B12 Bus	Front	-	-	●	●
	Wheelbase	-	-	●	●
	Rear	-	-	●	●
LSU Truck	Front	●	-	●	●
	Wheelbase	-	-	-	-
	Rear	-	-	-	●
NCHRP 659 garbage truck	Front	-	-	●	●
	Wheelbase	-	-	●	●
	Rear	-	-	●	●
NCHRP 659 Fire truck	Front	-	-	●	●
	Wheelbase	-	-	●	●
	Rear	-	-	●	●
Ambulance	Front	●	●	●	●
	Wheelbase	-	-	-	-
	Rear	-	-	●	●

It is also clear from Table 2, that the downhill driveway scenario presented more challenging for most of the vehicles. The crests generated by the direction changes in the slope, as well as the differential tire positions; cause the vehicle overhangs and the wheelbase to scrape the surface.

CONCLUSION

Based on the recommended grades presented in the GDGCR (1) for the driveway profile, the minimum ground clearances were calculated for the three TAC design vehicles and three LCV design vehicles. From the uphill and downhill driveway profile scenarios, the worst-case or minimum vehicle ground clearances at the wheelbase, front overhang, and rear overhang could be reverse engineered for the vehicles. In other words, these calculated values could help define the missing ground clearance values for the design vehicles in the GDGCR. However, upon using the same ground clearance values to analyze the driveway in a 3D environment, the findings showed discrepancies between the 2D profile and 3D analysis. It was observed that the basic analysis on a 2D profile is an oversimplified approach in modelling ground clearances and may produce inaccurate results. As the vehicle maneuvers a left or right turn into the driveway, each wheel is suspended at a different elevation on the 3D surface. As a result, the underside of the vehicle body is oriented accordingly, causing the ground clearance at the wheelbase and overhangs to differ. For example, in the scenario where the vehicle makes a right turn into an uphill driveway profile, the ground clearance at the front right corner bumper is minimized. Whereas, in the scenario where the vehicle makes a left turn into the same driveway profile, the ground clearance at the center of the front bumper is closest to the ground. In a left turn, the vehicle would have had the chance to straighten out parallel to the profile alignment. To establish the minimum ground clearances for the TAC design vehicles or the recommended grades, a similar study should be performed in 3D to determine the thresholds.

RECOMMENDATIONS

The minimum clearances identified in Section 1 helps to illustrate the differences between the 2D and the 3D analysis. While these minimum clearances seem to be sufficient to navigate the driveway vertical geometry, the 3D analysis, by incorporating both the turning maneuver and the ground clearances illustrate the opposite for most of the cases. 3D analysis is recommended to evaluate final designs; so that the turning of the vehicle is taken into account given the fact that the wheels travel at different grades as the vehicle executes the turn which can result in conflicts that cannot be identified in the 2D analysis.

Design vehicles play a crucial role in roadway and driveway design, the current design guidelines include a comprehensive set of vehicles in regards to turning characteristics, however, very little information is presented in regards to the ground clearances. This information is required in order to evaluate roadway components such as driveways and their vertical geometry. As a consequence of this geometry, a surface designed to accommodate a design vehicle with larger ground clearances than other vehicles that may require access, can cause damages to vehicles and infrastructure. We recommend that the existing design vehicles in the GDGCR should include information about their ground clearances. In addition to that the guidelines should also include low clearance and emergency vehicles.

As per the findings of this study, the inclusion of ground clearances for the existing design vehicles the GDGCR is recommended. Similarly, new vehicles such as the emergency and low clearance vehicles should be included as part of the standard design vehicles.

REFERENCES

1. Geometric Design Guide for Canadian Roads, Transport Association of Canada, Second Edition, September 1999.
2. J.L. Gattis, J.S. Gluck, J.M. Barlow, R.W. Eck, W.F. Hecker, H.S. Levinson, Driveway Design Issues in the United States. March 2010.
3. W.A. McConnel, Passenger Car Overhang and Underclearance as related to Driveway Profile Design, Part I-Vehicle Data – Washington D.C. 1958.
4. Bauer LA, "Passenger Car Overhang and Underclearance as related to Driveway Profile Design. Part II-Street and Highway Design Washington D.C. 1958.
5. R.W Eck and S.K. Kang, Low-C1earance Vehicles at Rail-Highway Grade Crossings: An Overview of the Problem and Potential Solutions. Washington D.C., 1991.
6. L. James French and R.W Eck, Development of Design Vehicles and Characteristics for the Hangup Problem; West Virginia Department of Transportation; May 2002.
7. Marc D. Williams, Daniel B. Fambro and Vergil G. Stover, The recommended design guidelines for the vertical alignment of driveways. Texas Department of Transportation TTI 990-2, 1991.
8. Herbert S. Levinson and Jerome S. Gluck, The Driveway Design Practices, Issues and Needs. 3rd Urban Street Symposium. June 2007.
9. National Cooperative Highway Research Program (NCHRP) Web-Only Document 151, Geometric Design of Driveways. Transportation Research Board, July 2009.
10. National Cooperative Highway Research Program (NCHRP) Report 659, Guide for the Geometric Design of Driveways. Transportation Research Board, 2010
11. John O. Sobajo, Design Guidelines for Highway Railroad Grade Crossing Profiles in Florida, Final Report – Florida State University.
12. Amy L. Clawson, Establishing Design Vehicles for the Hang-Up Problem; West Virginia Department of Civil Engineering. Master Thesis 2002.
13. Roads Construction 2012 Standard Specifications, Transportation Department The City of Calgary, ROADS Construction Division.
14. Fire Department Access Standard, The City of Calgary fire department. October 2008.
15. NEXUS Intersections 2.0, Transoft Solutions Inc.
16. AutoTURN PRO 3D 9.0, Transoft Solutions Inc.
17. Autodesk, AutoCAD 2013.