Swept Paths of Large Trucks in Right Turns of Small Radius

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ABSTRACT

When a large truck makes a turn of large radius, the driver may make a steady steering input and the swept path of the vehicle through the turn may be computed by an offtracking procedure. However, when a large truck must make a turn of small radius, such as a right turn at an urban intersection, the driver must devise a more complex steering input that minimizes intrusion of the vehicle into the space of other vehicles and also keeps the trailer vehicle units from encroaching on the curb. Determination of the steering input necessary for such a turn is defined as a steering-path problem. In this paper is described a purely geometric approach to the solution of the steering-path problem that results in steering inputs and swept paths typical of those observed in real turning maneuvers by large trucks. The method has been implemented as a computer program for IBM mainframe computers.

When a large truck makes a turn, the strategy used by the driver depends on some relationship among the turn geometry, the overall vehicle length, and the length and turning properties of the individual vehicle units. For purposes of discussion, only 90-degree turns of circular arc will be considered, such as the situation in which a two- or four-lane two-way road intersects with a four-lane two-way road (Figure 1). Such a turn would often be made after a complete stop, but that is not relevant to this discussion. The method to be presented is, however, quite general and may be applied in other situations.

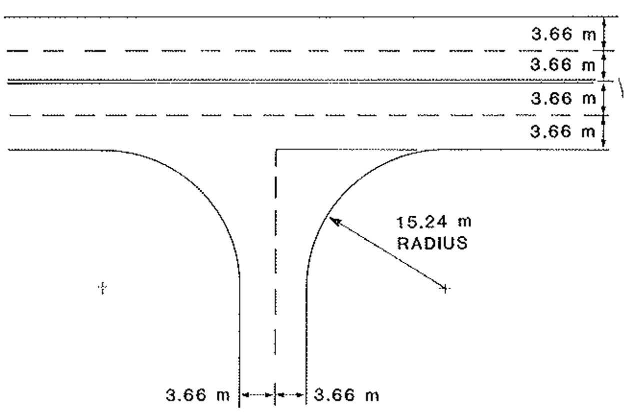

FIGURE 1 Typical intersection.

When a truck turns left at the example intersection, the driver may start from a central position in the entry lane and maneuver to terminate in the curb lane of the exit roadway, as shown in Figure 2. Such a turn typically would have a radius of 25 m or more. The driver simply steers such that the tractor steering axle follows a circular arc. The remainder of the vehicle combination follows, and its trajectory can be computed by the standard methods of offtracking (see "Vehicle Offtracking Models" by M.W. Sayers in this Record). There is generally enough space in the roadway intersection that the offtracking of the vehicle does not interfere with other traffic or obstructions such as curbs or islands. Such turns are straightforward because the turn radius is sufficiently large in comparison with the size of the truck and the roadway width that a steady steering input by the driver is all that is necessary to make the turn.

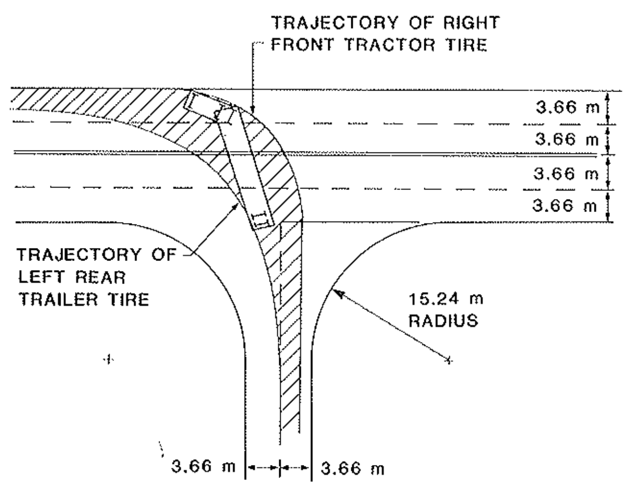

FIGURE 2 Left-turn trajectory of tractor-trailer at typical intersection.

An entirely different situation arises, however, when the truck turns right at the same intersection, as shown in Figure 3. The driver will usually move as far as possible to the left in the entry lane to increase the available radius. This radius could be further increased by moving even more to the left, if traffic would permit. [Such a move is considered hazardous because of the possibility that a following vehicle (cycle, motorcycle, or small car) also

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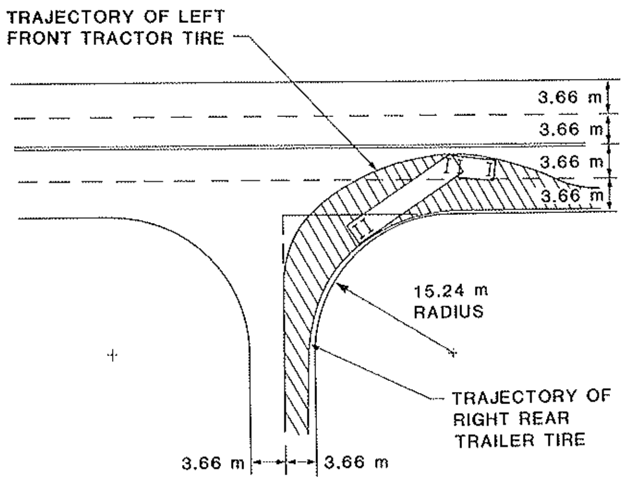

FIGURE 3 Right-turn trajectory of tractor-trailer at typical intersection.

intending to make the right turn might be tempted to pass inside the truck and would be trapped between the truck and the curb as the truck proceeded through the turn.] The truck driver negotiates the turn using a steering input that is intended to minimize intrusion of the tractor into lanes other than the exist lane and to keep trailing vehicle units from running over the inside curb. The steering input demands of the driver may be rather complex, especially for multiply articulated vehicle combinations--doubles and triples. The driver essentially has to solve an optimization problem, minimizing intrusion into other lanes while subject to the constraint of not running over the curb.

There is evidently a great difference between the steering input made by a driver in a right turn and that made in a left turn. This difference arises from the much larger left-turn radius, due to the available space of the oncoming traffic lane, that allows the driver to constrain the steering axle to follow a circular arc so that the rest of the vehicle will follow. For a right turn the driver generally constrains the rear axle of the vehicle to follow some path that comes close to but does not impinge on the curb, for at least some critical portion of the turn.

For a left turn the swept path of the vehicle can be determined in a straightforward manner by an offtracking procedure. However, for the small-radius right turn, no such procedure has been available. The steering-path problem is therefore defined as the determination of the steering input a driver must provide to make a right turn with the rear of the vehicle following the curb as closely as possible. This problem is unconstrained in the sense that the driver is free to make the turn subject only to the limitations that encroachment on the curb and movement to the left outside the entry lane are not permitted. A constrained steering-path problem, in which the driver would also be required to avoid obstacles such as other vehicles or islands, might be defined. This is considered much more complicated and is beyond the scope of this paper.

The steering-path problem may be addressed in several ways. It might for instance be treated as a multivariable optimization problem, a boundary value problem, or a feedback control problem. The latter might indeed be a rather instructive approach. A purely geometric approach, which depends on the assumption of a path for the rear unit of the vehicle traversing the curve, is described next.

STEERING-PATH PROBLEM

The steering-path problem is the determination of the driver's steering input in a turn when the rear of the vehicle tracks around a curve. If a path is assumed for the track of the turn center of the rear unit of the vehicle around the curve, the problem may be solved purely geometrically.

First, some definitions are necessary. A vehicle unit is a component of a vehicle that may steer or articulate relative to an attached vehicle unit. The tractor steering axle is, by this definition, considered a vehicle unit, and it tows the body of the tractor. Trailers and conventional converter dollies are also vehicle units, as are any self-steering axles attached thereto. A vehicle combination is a vehicle composed of a number of vehicle units, with the steering axle following some path prescribed by the driver and subsequent vehicle units in tow. An offtracking procedure is a computational algorithm by which the trajectory of the towed units of a vehicle combination may be obtained when the steering axle follows a prescribed path.

For purposes of this paper, the turning properties of a vehicle combination will be determined by following the common practice of using a zero-width "bicycle model" of the vehicle, in which each vehicle unit has an equivalent wheelbase or distance from its hitch point to turn center (see paper by M.W. Sayers in this Record). When a vehicle is driven at low speed along a prescribed path, the steering axle follows that path and at every point is tangential to it, if the small slip effects present are ignored. An offtracking procedure then permits the trajectory of the towed units of the vehicle to be determined. The offtracking procedure used in this paper is the method of pure pursuit. As the ith unit of a vehicle combination moves in small steps along the path, the problem is to find the position and orientation of the towed unit. This is done on the geometric assumption that the turn center of the towed unit ends on a line joining its new hitch point location and its previous turn center location. Other more sophisticated procedures are available and could as readily be used.

Now consider the steering-path problem. The key to this is the realization that, at every point through the turn, the turn center of the last unit of the vehicle combination is tangential to the specified path. At first, therefore, the steering path may be generated by an offtracking procedure with the vehicle reversed through the turn, as shown in Figure 4 for the rear trailer of a vehicle combination. This leads immediately, however, to three problems: First, if a towed unit, which in reverse tracking becomes a towing unit, has the hitch ahead of the turn center of the unit it is towing in reverse, then that unit is unstable and will simply perform a pirouette as shown in Figure 5. This usually arises for the tractor because of the location of the fifth wheel. This problem is overcome by making a shift of hitch point so that stability is obtained. Usually the shift required is small, no more than a few centimeters. The second problem is that units towed in reverse, and particularly the tractor, tend to cut inside the specified path initially as turning in reverse is commenced. This is actually what is required to back around a corner but is unrepresentative of a right turn. This problem is cured simply by modifying the path so that the tractor is not permitted inside the curb, as shown in Figure 6. A smooth transition may be inserted between the reverse offtracking and the modified paths. When the modified path has been established, the vehicle is driven forward to generate a swept path using an offtracking procedure. This may result in a minor

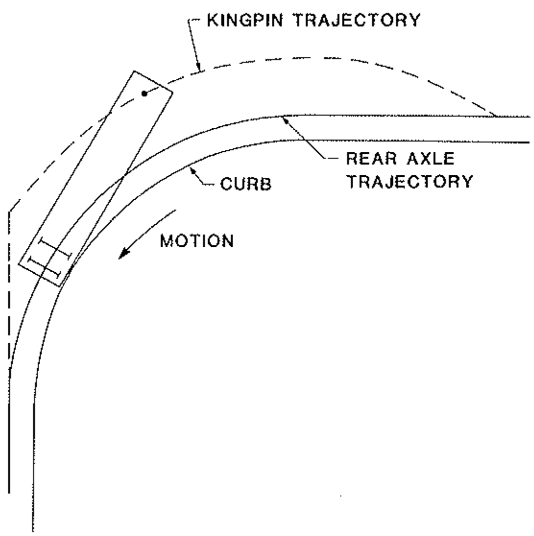

FIGURE 4 Locus of trailer kingpin as vehicle unit is backed with axle tangential to a specified curve.

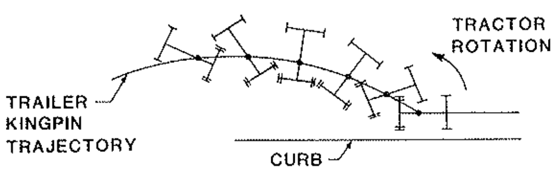

FIGURE 5 Tractor pirouette.

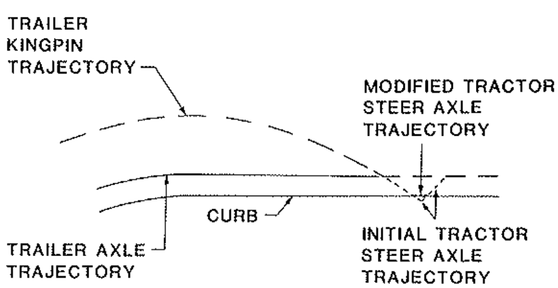

FIGURE 6 Modification of tractor path necessitated by reverse offtracking.

incursion (a few centimeters) of the the vehicle inside the specified path. The final problem arises during this forward offtracking step. For some combinations large steering angles, which exceed the steering angle limit, may be required. When the steering limit is reached in the forward offtracking phase, that steering angle must be held and the vehicle made to proceed forward in a steady turn until that turn trajectory meets the desired trajectory when a smooth transition is arranged onto the desired trajectory.

COMPUTER PROGRAM

The steering-path method outlined has been programmed in FORTRAN for an IBM 308X-series computer. The program proceeds in the following steps:

1. Define a coordinate system origin and define 251 rays at 1-degree angles from +10 to +260 degrees, as shown in Figure 7.

2. Define the curb as a 90-degree circular arc of given radius at the points where the curb meets the rays, also shown in Figure 7.

3. Specify the path of the centerline of the rear unit of the vehicle, either as a 90-degree circular arc or as a set of points measured from test data. In the former case, data points are defined on the rays. In the latter case, the given points are fitted by a series of cubic splines and data points are generated on the rays by solution for the point of intersection of each ray with the appropriate cubic spline curve.

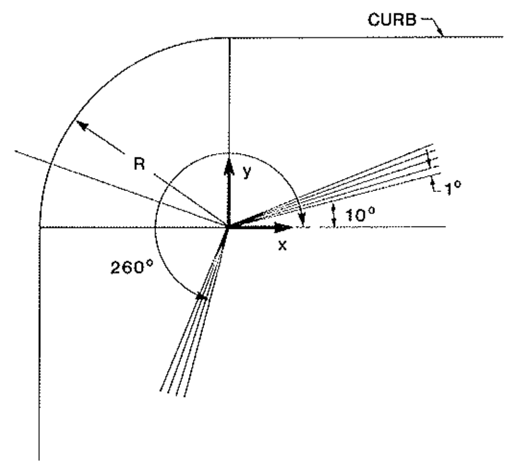

FIGURE 7 Coordinate system.

4. Define the geometric data for the vehicle.

5. Position the rear of the vehicle on the final (10-degree) ray, and perform the rearward offtracking procedure until the rear of the vehicle reaches the 260-degree ray.

6. Correct any inward incursion of the tractor inside the specified path, as described earlier.

7. Compute the required steering angle for the corrected path by using a cubic spline curve fit to the 251 data points of the path, which gives directly the tangent to this path at each point.

8. Wherever the steering angle exceeds the vehicle steering limit, produce a circular arc of the minimum steering radius until it meets the corrected path and arrange a suitable transition where the paths meet.

9. Drive the vehicle forward using the offtracking procedure along the modified path from Step 8 and develop the actual steering angle using the procedure described in Step 7.

10. From the hitch position of each towing unit, the orientation of each towed unit, and the edge geometry of each towed unit, compute a vehicle swept path as the innermost and outermost limits where each vehicle edge at each step of the offtracking procedure meets each of the rays. Then compute the clearance between the inside of the vehicle and the curb.

11. Print the results and store them for plotting.

The program was written to develop the method described in this paper. It is not considered suitable for highway geometric design purposes. It could be relatively easily modified in various ways, such adding curb- or path-generation methods to represent particular highway geometric design standards, building in the dimensions of standard vehicles used in highway geometric design, or including other off-

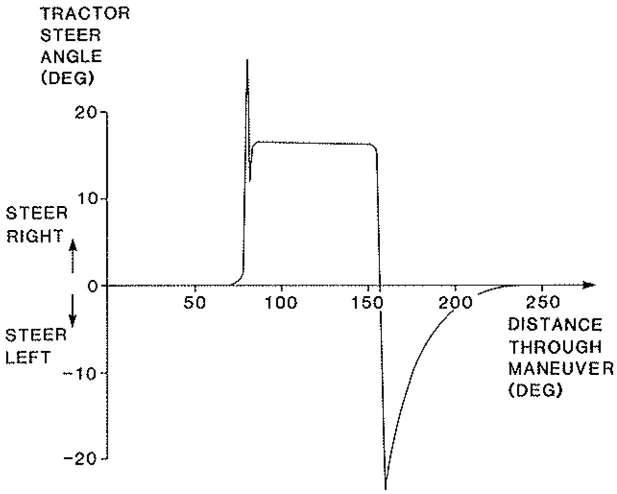

FIGURE 8 Tractor steering angle history in right turn of 9.144-m radius.

tracking procedures. The program takes only a few seconds to run. However, because of the accuracy necessary in this type of geometric computation, double-precision arithmetic is used throughout. Many large arrays are also used to simplify programming. The program is therefore not readily transferable to a microcomputer, though undoubtedly it could be with some modification to the flow of computation and some careful evaluation of the actual number of rays required for particular vehicles. The program will deal with vehicles of up to seven units, which is the conventional triple. It will not at present handle a multibranched chain of vehicle units, though again, that might not be a difficult modification.

Figure 8 shows the steering angle history of a tractor in combination with a 13.7-m (45-ft) semitrailer computed by this program in a 90-degree right turn of 9.144-m radius. This is clearly different from the steady value used in conventional offtracking procedures. It is of interest that the program of Sayer could be used to determine the steering path in a right turn by suitable choice of steering input segments through a series of iterations.

The major limitation of both the method and the program is that the user must specify the path of the rear of the vehicle. This path may not always be easily determined. Subtle variations in this path may also cause significant effects on the duration and magnitude of excursion out of the exit lane. Nevertheless, this method does reproduce the characteristic trajectory of the right turn, which is not readily possible with a direct offtracking procedure.

CONCLUSIONS

A method has been developed that permits computation of the swept path of a vehicle combination of arbitrary configuration as it makes a right turn of small radius. This method, the steering-path method, requires a good estimate of the path of the rear of the vehicle if the swept path is to be realistic. Such as estimate may, in some cases, be relatively easily obtained. The method has been programmed in FORTRAN for a large-scale IBM computer system.

The work to date demonstrates that there is a direct computational method for estimating the swept path of a truck combination in a small-radius right turn, a situation for which an offtracking procedure is often inappropriate. When fully developed, the method may be of interest where extended length combinations are required to travel to urban areas that have highway geometrics of a bygone standard.