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Review Article

2 + 1 Highways: Overview and Future Directions

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Most of the rural transportation system is composed of two-lane highways, and many of them serve as the primary means for rural access to urban areas and freeways. In some highways, traffic volumes can be not high enough to justify a four-lane highway but higher than can be served by isolated passing lanes, or can present high number of head-on collisions. In those conditions, 2 + 1 highways are potentially applicable. This type of highway is used to provide high-performance highways as intermediate solution between the common two-lane highway and the freeway. Successful experiences reported in Germany, Sweden, Finland, Poland, or Texas (US) may suggest that they are potentially applicable in other countries. The objective of this white paper is to provide an overview of the past practice in 2 + 1 highways and discuss the research directions and challenges in this field, specially focusing on, but not limited to, operational research in association with the activities of the Subcommittee on Two-Lane Highways (AHB40 2.2) of the Transportation Research Board. The significance of this paper is twofold: (1) it provides wider coverage of past 2 + 1 highways design and evaluation, and (2) it discusses future directions of this field.

1. Introduction

2 + 1 highways are used to provide high-performance rural highways as intermediate solution between common two-lane highways and freeways [1, 2] or as a safety countermeasure for two-lane highways [3, 4]. In two-lane highways, faster vehicles that want to travel at their desired speed face the on-coming traffic in the opposite lane and may suffer delays because of their inability to pass slow-moving vehicles. Thus, passing maneuvers are used by drivers to relieve drivers' stress, increase perceived level of service, and reduce delay [5]. On the other hand, passes are conditioned by the opposing lane occupation, which generates a conflict area. In fact, even though passing is not one of the main causes of crashes in two-lane highways, its consequences are severe [6]. Therefore, providing a continuous passing lane for each direction would reduce drivers' stress to find a passing gap on the on-coming traffic, as well as minimizing the likelihood of head-on collisions with opposing vehicles.

Experiences in Canada and Germany in the late 90s showed that 2 + 1 highways are a cost-effective solution where a two-lane road is not providing enough traffic efficiency and a four-lane roadway expansion seems unjustified due to demand, cost, or environmental issues [7]. Since then, it has been an increased interest on implementing 2 + 1 highway across the globe, either as intermediate solution before expanding to a multilane facility or as partial interventions to provide more passing opportunities.

2 + 1 highways provide a continuous three-lane cross section, which its central lane is used as passing lane alternatively for each direction (Figure 1). The main characteristics of 2 + 1 highways are as follows:

(i) Passing maneuvers are performed without opposing vehicles

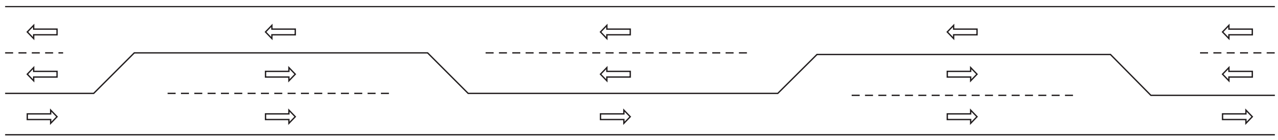

Figure 1: Schematic view of a 2 + 1 highway.

(ii) Travel directions are separated through a median, which could be physical or painted

(iii) Passing lanes are integrated along the segment rather than providing isolated passing lanes

There are two motivations to develop 2 + 1 highways, one targeting road safety and another one aiming for traffic efficiency, or both [8, 9]. In the case of Sweden, the main motivation of constructing 2 + 1 highways is to improve traffic safety, as many of the crashes on their rural network were head-on collisions due to runoff or control loss of the vehicle [4, 10]. Therefore, the main objective was to separate physically both travel directions. Nevertheless, restricting passing opportunities in the whole segment could lead to risky maneuvers performed by the delayed vehicles, despite the quite low traffic demands in Sweden. In order to reduce construction costs, common two-lane highways were converted to 2 + 1 highways by reducing lane and shoulder widths, and adding a median to allocate cable barriers. Road safety concerns have been also the main motivation of constructing 2 + 1 highways in Australia [11], Spain [12], or Wyoming, US [13], among others.

In the case of Germany, traffic efficiency was the main motivation of constructing 2 + 1 highways [14]. The rural network had low level of service at medium traffic demands, where passing opportunities are restricted by the opposing traffic stream. Under those conditions, providing passing lanes increases the level of service compared to common two-lane highways. In fact, the new Geometric Design Standards indicate that primary rural highways (EKL1) must have a 2 + 1 cross section [1]. The separation between both travel directions is achieved through one median painted in green, between the side markings. The lack of physical carriers is due to a lower relative importance of head-on collisions. The same motivation was present in South Korea [15] and Missouri, US [16].

Generally, the objectives of 2 + 1 highways are

(i) to reduce the risk of head-on collisions and thus improve road safety significantly compared to two-lane highways

(ii) to reduce delay due to the inability to pass, either from passing restrictions or limited gaps on the opposing traffic stream, and thus improve the level of service at medium traffic demands

(iii) to reduce the cost and environmental impact compared to conversion to freeways due to lower land occupation and less provision for structures

(iv) to increase average travel speed, when junctions at split level are designed

Despite the safety improvements of 2 + 1 highways, there are also operational and safety concerns. At traffic volumes close to capacity, vehicles on the passing lane face short gaps on the main lane while merging. They can contribute to head-on collision and provoke some drivers to continue passing at the transition zone or force vehicles on the base lane to brake. As a result, the number of conflicts in the merging area is increased and overall traffic efficiency is reduced. In this sense, merging areas act as bottlenecks that can reduce capacity and increase traffic conflicts at volumes close to capacity. Experimental studies have observed high speeds in passing lanes, in most of cases over the speed limit. Higher speed limits the capability of the driver to react under unexpected conditions, such as crossing fauna or slippery conditions. On the other hand, it can cause more conflicts with bicyclists or agricultural vehicles, which travel at a significantly lower speed.

Special attention should also be drawn to single-lane sections. On those sections, drivers are not allowed to pass. In some cases, it can lead to illegal passing maneuvers or to very long queues that may not be dissolved on the downstream passing lane. 2 + 1 highways can reduce or eliminate the opportunities to pass agricultural vehicles in single-lane sections, especially at retrofitted projects on which cross sections are not widened.

As a summary, some disadvantages of 2 + 1 highways include the following:

(i) Can reduce capacity

(ii) Can create safety concerns at traffic volumes close to capacity

(iii) Reduce the opportunities to pass slow vehicles in single-lane sections.

(iv) High speed in passing lanes, leading to more conflicts with vehicles with high speed differential, conflicts with fauna, or loss of control under slippery conditions

(v) Complex transition from one to two carriageways, which requires significant land occupation and work zones stage by stage. Similar conditions apply to two-lane highways

(vi) May require a separate network for slow-moving traffic, such as agricultural vehicles and cyclists

(vii) High cost and land occupation to accommodate split level junctions

Successful experiences reported in Germany, Ireland, Sweden, Finland, Denmark, Norway, Ireland, the US, Korea, and Japan may suggest that they are potentially applicable in other countries. In fact, there is an increasing interest on 2 + 1 highways in the US [2], Canada [17–19], Australia [20], New Zealand [21], Poland [22], Spain [12, 23, 24], or Mexico [25] that have written technical reports to assess the feasibility of implementing 2 + 1 highways and started their implementation in the last years [22, 26]. Nevertheless, there is no consensus on how to evaluate traffic and safety performance in 2 + 1 highways or how practitioners can implement them.

The objective of this review paper is to provide an overview of the past practice in 2 + 1 highways and discuss the research directions and challenges in this field, specially focusing on, but not limited to, operational research in association with the activities of the Subcommittee on Two-Lane Highways (AHB40 2.2) of the Transportation Research Board. The significance of this paper is twofold: [1] it provides wider coverage of 2 + 1 highways design and evaluation, and [2] it discusses future directions of this field.

The structure of the paper is as follows. Section 2 provides an overview of past practice in 2 + 1 highways in terms of design and evaluation of their road safety, capacity, and traffic operations. Section 3 summarizes the challenges that face researchers and practitioners to implement and evaluate new 2 + 1 highways. In Section 4, the feasibility of future directions for 2 + 1 highways studies is discussed. Two opposite directions—elaboration or simplification—are reviewed. Finally, conclusions and remarks on future directions are presented in Section 5.

2. Review of 2 + 1 Highways Design and Evaluation

2.1. Design Aspects. As mentioned above, 2 + 1 highways involve providing a continuous three-lane cross section on which the central lane serves as passing lane in alternate directions throughout the length of the facility. This configuration leads to unique design aspects that must be considered before their implementation. They include, but are not limited to, recommended AADT range and speed limit, passing lane length, design of transition areas, cross section, intersection and access design, and markings and signing.

2.1.1. Traffic Flow and Speed Limit. Kirby et al. [21] summarized the recommended AADT ranges and speed limits for international practice. Speed limits are between 80 and 100 km/h, while reported design speeds are between 100 and 110 km/h. As seen, 2 + 1 highways are usually recommended for medium and medium-high traffic volumes, even though it is not completely clear which are the most appropriate traffic volumes for them. Passing lane closures are implemented in Finland and Sweden at peak traffic conditions, such as weekend peaks [10, 27] (Table 1).

Another traffic variable to consider is the percentage or share of heavy vehicles. On the one hand, heavy vehicles have a lower desired speed and vehicle capabilities, thereby decreasing overall average travel speed [29, 34] and increasing the number of desired passes, having a direct impact on the expected traffic performance and safety. On the other hand, heavy vehicles also condition cross section design and left turn management and even can be a limiting factor to implement some types of 2 + 1 highways. It is important that designers provide land widths, turning radii, and other features, such as pavement, to accommodate trucks without impeding their access and ability to maneuver. Similarly, additional lengths may be required to accommodate passing convoys of heavy vehicles [35, 36]. Moreover, being a freight corridor can contribute substantially to the decision of implementing a 2 + 1 highway. For example, in the Utah DOT decision-making process for implementing passing lanes at US route 191, the freight corridor is worth 20 points out of a maximum of 120 points, compared to the scores for passing lanes that total between 35 and 66 points [37].

Table 1: Comparison of international 2 + 1 operational characteristics.

Country	Speed limit (km/h)	Design speed (km/h)	AADT (veh/day)
Sweden [10]	90–110	—	4,000–20,000
Norway [28]	90–110	—	6,000–22,000
Germany [1, 21, 29]	100	100–110	7,000–25,000
Finland [30]	100	—	8,000–13,000
Denmark [21, 31]	80–90	—	7,000–15,000
Ireland [8]	100	100	≤14,000
United Kingdom [32]	100	—	≤25,000
Austria (proposed) [21]	≤100	—	7,000–18,000
New Zealand [21]	100	—	10,000–25,000
Poland [22, 33]	100	—	10,000–25,000

Note. Values not reported on the references are indicated as "—."

2.1.2. Cross Section. Cross section is an important factor to evaluate the cost of implementing a 2 + 1 highway and its safety impacts. Initial applications in Sweden were based on restripping existing 13 to 14 m wide pavements, while in Germany only one-third have been reconverted through stripping [2]. The majority of German 2 + 1 highways are new construction, and most of them serve as primary routes and therefore have a wider cross section.

Table 2 summarizes the cross sections that are reported in international studies. There is a high variation in the carriageway width provision. The paved widths vary between 11 and 15 m. Generally, cross sections with cable barriers are wider than cross sections with painted median.

Figure 2 shows typical cross sections of the highest design standard of 2 + 1 highways in Sweden and Germany: types MML and EKL1, respectively. The cross section of a Swedish MML 2 + 1 highway consists of two 3.25 m lanes, one 3.50 m lane, 0.75 m shoulders, and 1.75 m median. Narrow traffic lanes have two objectives: to reduce the implementation cost and to reduce circulating speeds by narrowing traffic lanes. The total width of the single-lane section is 5.15 m to provide space for emergency stops and wider vehicles. Barriers include wide ropes, centerline rumble strips, or median barriers. Cable barriers are decided over paved median because they had the highest reduction on the number of fatalities in Sweden in the 90s: 80–90%

Table 2: Comparison of international 2 + 1 roadway cross sections.

Country	Median barrier	Width (m)				
		Single-lane	Two-lane	Paved shoulder	Median	Total paved
Swedish MML [10]	Yes	3.75	3.25	0.50	1.75	13.00
Swedish MLV [10]	Yes	3.25	3.25	0.75	1.00	12.25
German EKL1 [14]	No	3.50	3.25–3.50	0.50–0.75	1.00	15.50
German EKL2 [14]	No	3.50	3.25–3.50	0.50–0.75	0.50	15.00
Finland [21]	Yes	3.75	3.25–3.50	0.90–1.25	1.70	14.35
Finland [21]	No	3.75	3.25–3.50	1.25	0.00	13.00
Denmark [27]	No	3.75	3.50–3.75	0.50	1.00	13.00
Norway [28]	Yes	3.50	3.25	0.75–1.50	2.50	14.75
Ireland [8]	Yes	3.50	3.50	0.50–1.00	1.00	13.00
Ireland [8]	Yes	3.25–3.50	3.50	0.50	1.00	12.25
United Kingdom [32]	No	3.50	3.50	1.00	1.00	13.50
United Kingdom [32]	No	3.50	3.50	1.00	0.75	13.00
South Korea [15]	No	3.50	3.25	1.50	1.50	14.50
South Korea [15]	No	3.50	3.25	1.50	0.50	13.50
France	Yes	3.00	3.00	1.50	1.50	13.50
France	No	3.25	3.25	0.50	1.00	12.50
Poland [22, 33]	Yes	3.50	3.50	1.00	0.50	13.00
Poland [33]	No	3.50	3.50	1.00	0.50–1.00	13.00–13.50
Spain [12]	Yes	3.50	3.20	1.00–1.50	1.60	14.00
Spain [23]	Yes	3.50	3.25–3.50	1.50	1.00	14.25
Japan [38]	Yes	3.25	3.25	1.00	1.25	13.00
Texas, US [39]	No	3.35–3.65	3.35–3.65	0.90–3.00	0.00	11.85–16.95

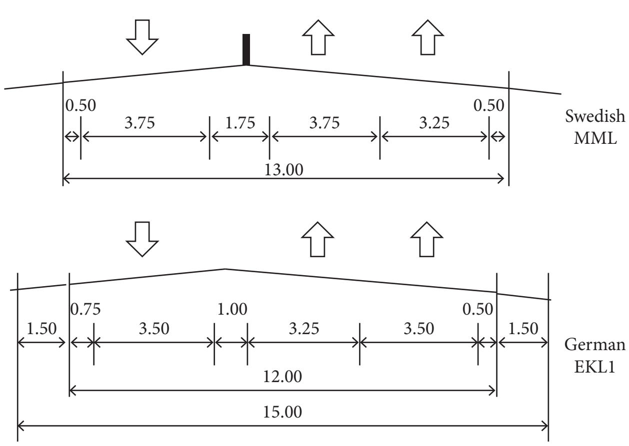

Figure 2: Typical cross sections of 2 + 1 highways in Swedish MML [10] and German EKL1 [14].

compared to 5% of paved medians. Given the scarce motorcycle traffic, cable barriers are not considered a safety issue. For MLV 2 + 1 highways, the cross section is narrower and includes three 3.25 m lanes, 0.75 m shoulders, and 1.00 m median. The total width of pavement is 12.25 m.

The typical cross section of a German EKL1 2 + 1 highway consists of two 3.55 m lanes, one 3.25 m lane, 0.50 m and 0.75 m shoulders, and 1.00 m painted median. It also provides additional 1.50 m of unpaved shoulder. Shoulders are narrower to avoid slower vehicles to move to the right side of their lane to allow illegal passing maneuvers in the left side of the lane. As discussed earlier, painted medians are preferred over cable barriers because of safety concerns. For EKL2 2 + 1 highways, the median is reduced to 0.50 m. The total width of pavement is 15.50 and 15.00 m, respectively.

2.1.3. Alignment. The alignment of 2 + 1 highways can differ depending on their main motivation. When new 2 + 1 highways are constructed to improve traffic efficiency, their alignment should be designed generous enough to accommodate higher speeds, generally between 100 and 110 km/h. In Germany, the design guideline indicates that travel speed for 2 + 1 highways is 110 km/h for EKL1 and 100 km/h for EKL2 [1]. In Ireland [32] and Sweden [10], design speed of new 2 + 1 roads is equal to 100 km/h. In Texas, US, and the United Kingdom, the design speed for 2 + 1 highways is the same as for two-lane highways: 65 and 100 km/h, respectively.

As result of design speeds between 100 and 110 km/h, the alignment is fairly straight, with very low bendiness (or degree of curvature) and curves with high radii. Desirable minimum stopping sight distance must be provided, although full overtaking sight distance is not required because the passes are only performed in the passing lane [32].

Two-lane highways that are reconverted to 2 + 1 highways usually have design speeds that vary among sections. Therefore, the alignment is usually less generous. As they may include sections with two-lane highways, overtaking sight distance is usually required along the entire facility.

2.1.4. Passing Lane Length. Passing lane length affects both the two-lane subsection and the single-lane subsections of the highway. On the one hand, the longer the passing lane section, the higher the number of passes and higher reduction in platooning, although the effectiveness rate typically drops off with distance. On the other hand, the longer the single-lane section, the higher the increase in platooning due to passing restriction. Therefore, the passing lane length should be an equilibrium between the benefits to the two-lane section traffic and the disadvantages to the single-lane section traffic, as well as a function of topography and location of junctions [32].

In Germany, typical lengths of passing lanes are between 1.0 and 1.4 km and should not exceed 2.0 km [2]. Irzik studied the optimal length of passing sections using observations in 15 2 + 1 highway sections in Germany [34, 40]. He found a strong correlation between the length of passing section, directional traffic volume, and share of incomplete dissolving processes. Specifically, the shorter the passing lane, the higher is the likelihood of having platoons dissolved at the transition. Applying the criteria, the minimum recommended lengths for directional traffic volumes of 700 and 1,200 veh/h are 1,070 and 1,300 m, respectively [40]. The maximum recommended length of 1,600 m was defined based on the percentage of followers on the single lane, which should not exceed 34.5% [40]. On a follow-up project, Lippold et al. [29] observed that passing lanes with lengths of 600 to 750 m were long enough to dissolve queues, while they maintained moderated speeds in the passing lane (20% of drivers exceed the 100 km/h speed limit). Medium length passing lanes (750–900 m) presented the highest speeds, compared to shorter or longer passing lanes, because drivers continued accelerating at the second half of the passing lane. Additionally, increasing the length of the prohibition for overtaking reduced average speeds. Average speed was governed by the slowest vehicle when the prohibition to overtake was longer than 2.5 km.

A summary comparing international passing lane lengths is provided in Table 3.

In other countries, practice has shown that passing lane lengths between 1.0 and 2.0 km provide acceptable operational and safety results in both directions of traffic. This range agrees with the TWOPAS simulation results of Szagala [43], who concluded that passing lanes between 950 and 2,000 m did not provide differences in PTSF combined for the whole range of traffic volumes. For Spanish conditions, Rodriguez-Martínez [24] studied the optimal passing lane length based on ATS, platooning, passing rate, and difference between maximum speeds on the single-lane and two-lane sections. Based on the Aimsun simulation results, she recommended passing zone lengths between 1,500 and 3,000 m, depending on the directional traffic volume. Specifically, the optimum range is between 1,500 and 2,500 m for 700 veh/h. Based on simulations, Cafiso et al. [42] recommended minimum passing lane length of 800 m, to minimize the number of conflicts per km. For traffic volumes higher than 800 veh/h, the recommendation increases to 1,000 m.

Table 3: Comparison of international passing lane lengths for 2 + 1 highways.

Country	Passing lane length (m)	Notes
Sweden [2]	1,000–2,000	Depends on alignment and intersections
Germany [14]	1,070–1,600	For directional traffic volume of 700 veh/h
Germany [3]	600–1,2000	Should not exceed 4,000 m
Denmark [27]	1,000–2,000	Recommended value of 1,500 m
Norway [28]	1,000–2,000	Depends on AADT
Ireland [8]	1,000–2,000	Relaxations are permitted from 800 to 3,000 m
United Kingdom [32]	800–1,500	Relaxations are permitted from 600 to 2,000 m
United States [9, 41]	1,300–3,200	Depends on AADT
United States [9]	1,500–3,000	Depends on AADT
Spain [24]	1,500–3,500	Depends on AADT, based on simulations
Poland [42]	800–1,200	Depends on AADT, based on simulations
South Korea [15]	800–1,500	—

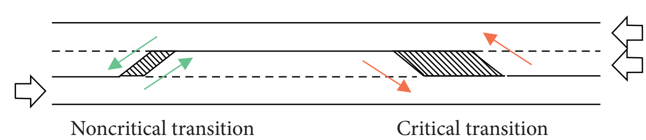

Figure 3: Critical and noncritical transitions on 2 + 1 highways.

2.1.5. Transition Zone Length.

2.1.5. Transition Zone Length. There are two types of transitions on 2 + 1 highways: critical and noncritical [2]. A critical transition is located immediately downstream of a lane drop, while a noncritical transition is located immediately upstream of a lane addition (Figure 3).

At the critical transition, vehicles in the passing lane are merging to the single lane and can head toward the opposing traffic. At the noncritical transition, vehicles are diverging to the passing lane and head away from each other. Based on observations in Germany, only about 1.7% of passing processes involved driving over the ghost island [34]. The percentage can increase as the percentage of trucks increases. Therefore, a substantial buffer between the vehicles traveling in opposite directions is needed [2].

Given the total length of the 2 + 1 segment, the longer the transition zones, the shorter the effective two-lane subsections. Existing passing lane standards may lead to large transition zones and therefore shorter two-lane subsections.

Table 4 summarizes the international design criteria for transition zones. The main differences are observed at the critical transition, ranging between 180 m in Germany and 500 m in Finland. They usually include two tapers and a buffer section, while the noncritical transition only uses tapers. The range for noncritical transitions is narrower and varies from 50 to 100 m.

2.1.6. Intersections and Access Control. Intersections and accesses require careful consideration with respect to their locations on a 2 + 1 highway. 2 + 1 roads can operate safely and effectively in areas where minor intersections and driveways provide direct access to the roadway. However, split level intersections could be preferred at the highest functional class of 2 + 1 highways, like for German EKL1 [1]

Table 4: Comparison of international transition zone design.

Country	Transition zone length (m)					
	Critical transition			Noncritical transition		
	Taper	Buffer	Total	Taper	Buffer	Total
Sweden [2]	150	0	300	50	0	100
Germany [14]	3	174	180	30	0	60
Denmark [27]	140	0–300	280	25	0	50
Finland [21]	200	100	500	25	0	50
Ireland [8]	150	0	300	25	0	50
United Kingdom [32]	130	40	300	25	0	50
Texas, US [41]	WS/3.28	15	Variable	WS/2/3.28	0	Variable

Note. W is the lane width in ft; S is the posted speed limit in mph.

or at relatively high traffic flows in the UK [32]. This decision was taken because the observed 2 + 1 highways with split level intersections had the most favorable accident cost rates and the most uniform speed levels [34] because at-grade intersections force drivers to reduce speed or even to stop.

In some design guidelines [8, 32], it is stated that the design must minimize the number of intersections in order to avoid standing vehicles and concentrate turning movements. Further, it could be required to connect side roads and accesses to a collector road running parallel to the 2 + 1 highway, such as in the UK [32].

Major intersections should generally be located in the buffer areas between passing lanes in opposing directions of travel and should have left-turn lanes provided [1, 26, 32, 34]. The intersections vary from priority intersections, U-turn facilities with left turn, at-grade roundabouts, or compact grade separation [8]. Left turns off the major road are only permitted at priority junctions located at single-lane sections, while left turns onto the major road are not permitted [8].

U-turn provisions are ideally provided at junction locations, and one of the easiest ways is a roundabout [20, 23]. When the number of heavy vehicles is significant, at-grade roundabouts shall be avoided to minimize the impact on traffic performance, given that capacity of a roundabout is significantly decreased when the share of heavy vehicles increased [33].

2.1.7. Marking and Signing. Marking and signing of 2 + 1 highways usually follows general regulations for two-lane highways [1, 21, 32] with passing lanes and adds some nonprescribed signs for additional information. In this sense, it must be indicated:

(i) Presence of one passing lane before the noncritical transition
(ii) End of the passing prohibition before the noncritical transition
(iii) End of the passing lane before the critical transition
(iv) Start of the passing prohibition before the end of the critical transition

The distance between sections and signals depends on the general regulations of each country. For example, in Sweden, the end of the passing lane is indicated 400 m before the start of the taper from the critical transition and at the start of the taper from the critical transition [10]. In Germany, the same sign is indicated 400 and 200 m before the start of the taper [1], while in Finland it is located in the beginning, in the midpoint, and 400 m before the end of the passing lane [30].

One of the most important additional sign is the advance information on when the passing lane starts and how long it is. This sign is used to reduce frustration due to passing prohibition and encourage drivers to delay passing until the passing lane is approached [14, 23, 30, 32]. Other additional signs can be located at the end of the passing lane to indicate the length of the prohibition to overtake. Based on field observations of passing times, Kaistinen et al. [30] also recommend to include signs that urge to use the passing lane only for passing, as more drivers might be able to pass on the same length.

Marking of rural highways is enforced at the German Design Guideline [1]. Standardized cross sections and markings help the driver to identify which type of highway they are driving at without depending on road signs. Self-explaining roads increase the probability of encouraging the desired driver behavior and do not rely on the drivers' ability or willingness to read and obey road signs [44]. Specifically, German EKL1 2 + 1 highways are painted with a green median, while EKL2 have a white median. In Spain, medians are painted in red [23], while in Denmark they are stripped in white [27].

At the end of the passing lane, arrow markings in the pavement should point to the base lane, to encourage drivers to leave the passing lane [3, 30].

3. Evaluation of 2 + 1 Highways

3.1. Road Safety. 2 + 1 highways are designed to perform passing maneuvers without opposing vehicles, during the two-lane subsection. This fact avoids the risk of head-on collisions during passing maneuvers. Moreover, the presence of physical barriers in some countries also reduces the head-on collisions due to runoff or accidents caused by fauna crossing the highway. Fatal crash reductions, compared to two-lane highways, range between 0 and 90% (Table 5).

In Ireland [46], they compared the number of fatal accidents and number of accidents at different facility types:

Table 5: Comparison of international 2 + 1 road safety performance.

Country	Median barriers	Crash reduction (compared to two-lane highway) (%)		
		Fatal	Fatal + injury	All
Sweden [45]	Yes	76–82	55–60	—
Sweden [45]	No	35–40	35–40	
Sweden [10]	Yes	80–90	—	—
Finland [2]	Yes	46	25	—
Finland [2]	No	0	11	—
Germany [2]	No	—	36	28
Denmark [27]	No	50	—	—
Denmark [27]	No	0	76	—
United States [13]	No	—	27	44

two-lane highways, dual carriageways (2 + 1 highways and multilane highways), and motorways (or freeways). They calculated the ratio between the accidents in a given facility and the accidents in motorways. The ratio of fatal accidents was equal to 2.8 and 6.7, for dual carriageways and two-lane highways, respectively. Considering all accidents, dual carriageways had a ratio of 2.9 and two-lane highways had a ratio of 4.6. Comparing two-lane highways and dual carriageways, two-lane highways have 1.6 times more accidents (4.6/2.9) and 2.4 times more fatal accidents (6.7/2.8). Therefore, severity in two-lane highways is higher than that in other facilities. Dual carriageways have similar severity than motorways.

Berger analyzed German crash data by facility type and developed crash rate models depending on daily traffic (AADT) and facility type [47]. Two-lane highways presented higher crash rate than 2 + 1 highways and multilane highways. Specifically, for 10,000 veh/day, the crash rates were equal to 1.3, 1.11, and 0.9 crashes per 1 million vehicle-km travelled. The differences are lower than the observed in Ireland, but they include mobility (vehicle-km travelled).

In Arkansas, US, it was observed that the crash rates on three 2 + 1 highways were lower than the statewide average for rural two-lane highways [9]. In Wyoming, US, crash data were collected over a period of 17 years to calibrate safety performance functions and crash modification factors for passing lanes [13]. The results indicate that total crash rate was reduced from 0.86 crashes per million vehicle miles to 0.48 crasher per million vehicle miles, representing a 44% reduction for the areas with passing lanes. At the entire study section, the reduction was 21%. For the crashes with fatalities and/or injured, the reduction was 27% at the passing lane sections and 22% at the entire facility.

Finally, Cafiso et al. [42] estimated the number of conflicts along the passing lane as surrogate performance measure of safety using traffic simulations. Short passing lanes (500 m) had the highest number of conflicts per km, for all traffic volumes, while passing lanes longer than 800 m did not reduce much the number of conflicts per km. As a result, minimum passing lane length of 500 m is recommended to be increased to 800 m. On the other hand, the number of conflicts increased with traffic volume, and the increase is exponential for volumes higher than 800 veh/h. Only passing lanes of 1,000 or nor presented linear increase after 800 veh/h.

Despite the safety improvements of 2 + 1 highways, there are also safety concerns, especially on the critical transition zone: the merge transition zone immediately downstream of the passing lane section. At this section, late passing maneuvers can contribute to head-on collisions and provoke some drivers to continue passing throughout the entire hatched merge zone. In Denmark, 24% of all accidents occur on transition sections [27], and they usually involve vehicles in the same direction. In Sweden, the conflicts on the critical transition zone with moderate traffic demands lead to closing the passing lanes in weekend peaks [10]. In Finland [30], the amount of brakings was used to measure conflicts at the end of one passing lane. Brakings increased with traffic volume: when the traffic volume was higher than 1,000 veh/h, 50% of the passing vehicles had to brake. At 1,400 veh/h, it was very difficult to return to the base lane. The simulations for Poland also indicate that the majority of conflicts take place at a distance of 100 m before the end of the passing lane [42].

Long single-lane subsections can increase considerably platooning that cause delay and frustration to drivers. In such conditions, illegal passing maneuvers can be triggered. It was observed in Germany that prohibition of overtaking longer than 4 km increased the number of illegal passing [29]. As consequence, most of the guidelines and studies limit the passing lane maximum length. For example, Gattis et al. [9] for Arkansas and NRA from Ireland [8] indicate that agencies should reexamine the need for passing lanes longer than 3 km.

It should be noted that reducing the carriageway width can increase the number of accidents involving vehicles traveling alongside in the same direction on the single-lane section [34].

3.2. Capacity and Traffic Performance. Capacity of 2 + 1 highways is usually governed by the capacity of the single-lane subsections. There is no international consensus on how 2 + 1 highways affect capacity. In Sweden, capacity of 2 + 1 highways with median barrier decreases around 20%, compared to two-lane highways, caused mainly by merging conflicts at the critical transition zone [10]. Similar results were observed in Finland [30], where traffic jams occurred after the longest single-lane section of the 2 + 1 highway. The hypothesis was that merging conflicts caused disturbances that caused the start of the break down.

On the other hand, recent simulations in LASI 2 + 1 of German 2 + 1 highways resulted in an increase on capacity around 15% [14], while previous field studies indicated a reduction of capacity to 1,400 veh/h [30, 34]. For operational analyses in Denmark, capacity of two-lane highways is set at 1700 pc/h and capacity of 2 + 1 highways is 1900 pc/h [27]. They observed that 2 + 1 highways perform well for traffic demands lower than 1600 pc/h. For higher traffic demands, the 2 + 1 highways reach capacity on the single-lane subsection and speeds are kept very constant and capacity/breakdown is not reached on the two-lane subsection. At near-to-capacity conditions, speeds on the transition zone were reduced to 20 km/h and 20% of drivers still tend to pass using the passing lane, causing breakdowns (Table 6).

The main impacts of 2 + 1 highways on traffic performance are derived from the possibility of passing using the passing lane. This fact increases the number of passing maneuvers, reduces the percentage of following vehicles, and increases average speeds, for low to medium traffic demand. Table 7 summarizes international experience on speed impacts of 2 + 1 highways.

Practically in all the cases, average speed increases. The speed increase is located mainly on the two-lane subsection, while speed is reduced on the single-lane subsection around 15 km/h. The highest speed differences are produced in South Korea [49] and Poland [50], where the speed was compared at the beginning and the end of the two-lane subsection. On the other cases, average speeds along the complete segment produced speed variations between 1 and 10 km/h. In Japan, simulation results indicated that average travel speed increased between 8 and 14 km/h after adding auxiliary passing lanes.

When evaluating the speed at the passing lane, field observations found that the majority of vehicles drove over the speed limit. In Finland, observations from an instrumented vehicle indicated that more than 80% of the passing vehicles exceed the speed limit of 100 km/h [30]. Similar results were found in Germany [3]. They also distinguished speeds depending on the passing lane length. For passing lanes over 900 m, 85th percentile of speed was 132 km/h, while for shorter passing lanes, 85th percentile of speed was 122 km/h.

Table 8 summarizes the average variation on the percentage of following vehicles, which depended on the passing lane length and traffic compositions. The highest variations are produced in Germany and the US. In Germany, short passing lengths between 600 and 750 m were long enough to dissolve queues formed in the single-lane section [3]. Usually, the greatest benefits from passing lanes appear to be within the first kilometer of their length [9, 34, 51]. In fact, most of the recommendations limit the passing lane length to 2,000 m (Table 3), only being extended to up to 3,500 m in simulation studies. In fact, some guidelines limit passing lane lengths to reduce drivers' stress on the single-lane section [3, 8, 9].

Table 6: Comparison of capacity impacts of 2 + 1 highways.

Country	Capacity (veh/h)	
	2 + 1 highway	Two-lane highway
Sweden [10]	1,500	1,600–1,700
Germany [14]	1,300–1,400	1,600–1,700
Finland [2]	1,600–1,700	1,600–1,700
Finland [30]	1,400–1,500	—
Denmark [27]	1,900	1,700
South Korea [48]	2,000–2,150	—

Table 7: Comparison of speed impacts of 2 + 1 highways.

Country	Median barriers	Average speed variation (km/h)	Speed at passing lane (km/h)
Sweden [45]	Yes	+2	
Sweden [45]	No	+4	
Sweden [10]	Yes	+10	
Finland [2]	Yes	+1	
Germany [2]	No	+5 to +10	100–130
Germany [29]	No	+5 to +10	100–120
Denmark [27]	No	-3 to +4	
Finland [30]	No	—	100–130
South Korea [49]	No	+20 (one section)	
Poland [22]	No	+10 (one section)	
Japan [38]	Yes	+8 to +14 (simulation)	
United States [9]	No	Modest	

Table 8: Comparison of percentage of following vehicles on 2 + 1 highways.

Country	Median barriers	Following vehicles variation (%)
Germany [21]	No	−15
Germany [3]	No	−23 to −2
South Korea [49]	No	−8 (one section)
Poland [22]	No	−7 (one section)
United States [2]	No	−28 to −15
United States [9]	No	−14

4. Challenges on 2 + 1 Highways

Planning, designing, and maintaining a 2 + 1 highway present several challenges that do not arise in other rural facilities. Moreover, there is no agreement on their evaluation or any simulation guidelines. The challenges that researchers, practitioners, and agencies face can be classified into four main categories: (1) typology and implementation criteria, (2) design aspects, (3) performance measures, and (4) simulation tools.

The first challenge is to determine whether a 2 + 1 highway should be implemented or not, and how. The main motivation could be road safety, traffic efficiency, or both. In some cases, 2 + 1 highways are constructed as a road safety initiative to provide more passing opportunities when traffic volumes are too low to justify building a divided carriageway. In other cases, 2 + 1 highways are constructed as an intermediate step for a future divided highway. Planning and designing shall be in accordance with the ultimate goal of the facility. Based on the German and Swedish classifications, we propose the following three classes:

(i) Class I 2 + 1 highways are highways where motorists expect to travel at relatively high speeds. The alignment is designed with design speed of 100 km/h, and it provides continuous three lanes without left turns. They are similar to German EKL1 and Swedish MML.

(ii) Class II 2 + 1 highways are highways where motorists do not necessarily expect to travel at high speeds. 2 + 1 sections are alternated with 1+1 sections and the alignment is designed with variable design speeds. Some intersections could be placed to allow left turns. They are similar to German EKL2 and Swedish MLV.

(iii) Class III 2 + 1 highways are highways where motorists do not necessarily expect to travel at high speeds and lane widths are narrowed to accommodate the third lane. It is not expected to provide higher speed than a two-lane highway and is implemented mainly to improve road safety.

The types depend on the cross section, alignment, and traffic control elements (Table 9).

It is a challenge to determine which type of 2 + 1 highway fits better to the objectives of the action and its budget. Expected performance and level of safety should be addressed, as well as design requirements. They include, but are not limited to, traffic volume, presence of heavy vehicles, possibility of widening the platform, intersection density, or design speed. Utah DOT [37] documented their decision-making process to add passing lanes to a two-lane highway depending on traffic volume, heavy vehicles' volume, crash history, status as a freight corridor, and the existing length between passing lanes. Kirby et al. [21] prepared an evaluation process to assess the benefit-cost ratio of implementing 2 + 1 highways depending on terrain type, traffic volume (AADT), percentage of heavy vehicles, and length and spacing of passing lanes. Recently, Cheng et al. [52] developed another framework to perform cost-benefit analyses of providing auxiliary passing lanes on two-lane highways based on traffic simulations and questionnaires. Benefits included the reduction of crash-related costs and saved time per kilometer, while costs included construction and maintenance. As seen, the prioritization criteria are not homogeneous. More research is required in this sense, in order to incorporate road safety criteria as performance measure and also more design parameters, such as design speed, cross section, or intersection density.

In using existing uninterrupted flow two-lane highway segment techniques, road authorities get poor or even failing level of service results in medium traffic volume situations. This often leads to costly roadway expansions and excessive highway widening in small sections in order to meet level of service standards. By having more appropriate level of service measures for these types of facilities, road authorities can better allocate their scarce resources. Moreover, the methodology should be easy to apply and with performance measures that are compatible across rural highways, in order to facilitate region or statewide analyses and distribution of the resources.

Expected performance can be estimated based on one or more performance measure. It is still open for debate which would be the most appropriate performance measure(s) for evaluating traffic efficiency and road safety in 2 + 1 highways. Only the German Highway Capacity Manual [53] establishes a procedure to evaluate quality of flow in 2 + 1 highways. Some authors have used speed variation [2, 10, 15, 22, 45, 48] or speed differential on the 2-lane and 1-lane sections [50], while others have used the percentage of platoons dissolved [2, 21, 34, 40, 49] or the time-to-collision distribution [22, 33]. It is still unclear which performance measure(s) could be used for Class II and Class III 2 + 1 highways, on which 2 + 1 sections alternate with conventional two-lane highways. In this sense, it is required more research and discussion to select the performance measure(s), to define a methodology to evaluate 2 + 1 highways as a whole, and to propose thresholds for determining the quality of service depending on the type of 2 + 1 highway. Theoretical, empirical, or simulation-based speed-flow relationships or density-flow relationships could be developed, like for two-lane highways.

The experience in other countries can be used as starting point to design our facility. They provide a framework to understand the ranges on expected traffic operations and road safety, as well as on design aspects. During the design phase, the designer choice on length and spacing of the passing lanes accounts for even more variations in route operational characteristics and increases the need for more reliable simulation tools. This is especially the case, if two-lane highways are enlarged to 2 + 1 highways on a step-by-step basis. Current simulation tools have incorporated passing maneuvers using the opposing lane, as well as lane changing. However, merging behavior is adapted from freeways and could not represent well the conflicts at the transitions, especially at volumes close to capacity [15, 22]. Further, Kaistinen et al. [30] indicated that passing times in 2 + 1 highways are longer than in two-lane highways, which could lead to a specific passing model for 2 + 1 highways. More reliable simulation tools will require a profound review of drivers' behavior, as well as including the calculation of the performance measure(s).

Other important design criteria are the width of the lane on the single-lane section and the separation between the two travel directions. Providing a narrow single lane can remove passing opportunities to agricultural vehicles or slow trucks during the single-lane section and reduce the efficiency of the facility, especially if the passing lane length is high. Separation between two travel directions could be without barrier, with concrete barrier or with cable barriers. Both construction and maintenance costs shall be accounted when selecting the separation: while cable barriers could be cheaper to construct, they have higher reparation costs [10, 21, 33]. Similarly, the convenience of providing passageways should be considered: mobile or removable barriers will provide more flexibility to create passageways when required.

5. Directions for Further Study of 2 + 1 Highways

As the previous review indicates, the study and implementation of 2 + 1 highways have generated a few challenges that need to be addressed. In this section, we discuss the

Table 9: Proposed classification of 2 + 1 highways.

Characteristics		Class				
		I-a	I-b	II-a	II-b	III
Alignment	Could be divided in the future	Yes	No	No	No	No
	Target speed (km/h)	100	100	Variable	Variable	Variable
Number of lanes	Continuous three lane	Yes	Yes	No	No	No
	Alternating 2 + 1 and 1+1 sections	No	No	Yes	Yes	Yes
Cross section	Can be widen without restrictions	Yes	Yes	Yes	Yes	No
	Limited widening (1 m)	No	No	No	No	Yes
Left turns	Intersections	No	No	Yes	Yes	Yes
	Roundabouts	No	No	No	Yes	Yes

potential directions for further study of 2 + 1 in the context of performance evaluation and implementation factors: how more flexible, complex, and intense modeling can provide performance estimates, and how a simplified approach can provide hints of estimated performance.

5.1. More Flexible, Complex, and More Intense Modeling. Future directions in traffic performance and safety evaluation usually rely on traffic microsimulations, even though experimental or field studies depict observed, under operation, conditions. Unfortunately, field measurements can be expensive and most importantly, they rarely provide sufficient repeatability for the full range of traffic demands, so the conclusions may only be applicable to the observed conditions. Moreover, they can only be carried out after the 2 + 1 highway has been opened to traffic. At this point, traffic microsimulation must be considered.

Current simulation tools, such as VISSIM, Aimsun, TRANSMODELER, CORSIM, TWOPAS, or LASI, can microscopically represent drivers' behavior on the highway, including car-following, lane changing, passing in the opposing lane, merging, or speed reduction in curves [54–58]. The embedded models function with parameters that have been calibrated for two-lane highways or freeways. The list of potential improvements to the models is long, such as speed reductions due to narrower lanes or due to higher presence of sharp curves, merging behavior at the end of the passing lane with short gaps on the base lane, different passing behavior with longer time on the passing lane or speed and platooning variations due to intersections or accesses.

At this point, field data are necessary to better represent drivers' behavior in 2 + 1 highways and to verify the transferability of the results among sites and countries. To collect behavioral data, traditional approaches include automatic detectors [59], roadside observations [9, 40], instrumented vehicles [30], driving simulators [47], or even video recordings from drones [60]. Alternative data sources should be explored as well, such as utilization of big data and global datasets. Big data can provide invaluable information to validate the theory in this information age. Accuracy and reliability of big data shall be considered in light of the required resolution in the models.

Model developers need to be aware that complex models tend to have higher requirements not only for data but also for the model user. The education of the next generation of modelers need to keep up with complexity in modeling, and vice versa, model developers should account for the capability of future model users and data availability when deciding on complexity.

Simulation tools also need to output the performance measures for evaluation and with the adequate resolution. Not providing the required measure(s) can discard one tool over another. Further, requiring headways with a tenth of a second accuracy will discard older tools, on which simulation steps are equal to one second. This is especially relevant to calculate percent followers. Currently, the threshold to determine the following conditions is 3.0 seconds [61], but other studies suggest that this value should be between 2.5 and 2.6 seconds [62, 63]. This fact is even more relevant in safety analyses because most of the traffic microsimulation tools do not account for traffic conflicts, such as time-to-collision.

5.2. A Simplified Model for Facility, Regional, or National Assessment. Agencies usually count on scarce resources that should be distributed among several actions. A tool that can incorporate several facilities that represent region or nationwide networks could facilitate the decision-making process and prioritize the investments. Recent development of various global datasets including transportation networks, such as OpenStreetMap, can facilitate the application of regional or national estimations. Of course, the datasets may not be sufficient to calibrate the more complex models, as they may not accurately represent passing opportunities or alignment restrictions. This would suggest the need for simplified models requiring less data, which capture the essence of traffic performance on rural highways.

For this research, revival of primitive models or simplification of complex models would be needed: a simplified model is required to make it operational and easy to apply. One example is the speed-flow relationships that are included in the German Highway Capacity Manual (HBS) [53] or the proposed for the Korean Highway Capacity Manual [15]. They input basic traffic and alignment data and provide expected average travel speed and density. Similarly, other HCM or HBS speed-flow, density-flow, or number of passes-flow relationships can be developed based on theory, simpler rules, field data (as they have been developed for two-lane highways [59, 62, 64–67]) or simulation studies. Key alignment inputs to consider while developing such speed-flow relationships should include type of 2 + 1 highway, horizontal and vertical alignment class, passing lanes lengths, transition lengths, lane widths, and intersections. Key traffic inputs are directional traffic volume and percentage of heavy vehicles.

For planning purposes, alignment and traffic data are vaguer. Most of the times, practitioners only have terrain type and expected annual average daily traffic as inputs. In this sense, ranges of expected alignment inputs shall be developed from planning inputs in order to be able to apply the simplified model.

6. Conclusion

This paper makes a significant contribution to the body of knowledge by reviewing the current research and practice in 2 + 1 highways, as well as by identifying challenges in this field, which can be classified into (1) typology and implementation criteria; (2) design aspects; (3) performance measures; and (4) simulation tools.

After discussing in detail the challenges, we provide future directions of the research and research needs. While we can advocate for more behavioral studies and more intense modeling to better represent drivers' behavior in 2 + 1 highways, we can also step back and develop basic relationships for planning processes, where the amount of information regarding the final design of the highway is rather vague, or for regional analyses. The findings from both approaches could be cross-referenced. While the first approach may need complexity and elaboration, the second approach could be not detailed enough for designing. A simplified model could be validated against more complex tools and/or empirical data, or reversely, microscopic models can be used as theoretical background for a simplified model. These two directions for research and practice are complementary and should coevolve.

Finally, we note the limitations of this paper. This review paper did not review the complete history of 2 + 1 highways nor listed all the countries with 2 + 1 implementations or all their design aspects. We did not discuss implementation factors in detail, heavy vehicles' impact, or simulation tools' capabilities. Further studies should discuss and benchmark the simulation tools in the context of 2 + 1 highways. It is expected that the ongoing research will improve simulation tools and provide analysis procedures and implementation toolkits for this specific highway type, which will be in the interest of agencies with scarce resources and researchers with limited field data.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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