Bicycle Use of Highway Shoulders

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Paving highway shoulders offers benefits that include the safe accommodation of bicycles. Although there is much current interest in developing policies and plans for designating bicycle routes based on paved shoulders, there is a lack of methodology for quantifying bicycle-related benefits for inclusion in economic feasibility studies. This article reports research in opportunities and issues in the use of highway shoulders for bicycle routes. Information on existing policies and designs was compiled and summarized from a survey of provincial and state transportation departments in Canada and the United States and from a review of the literature. Design factors for partially and fully paved shoulders are noted from the perspective of bicycle travel. The treatment of safety factors includes issues such as common use of travel lanes and the aerodynamic effects of heavy vehicles and speed on bicyclists. A risk analysis of bicycle-related collisions is presented. Accident reduction benefits attributable to shoulder bikeways are quantified in economic terms. The economic feasibility of partially and fully paved shoulders featuring bikeways and rumble strips is reported. The results show that the inclusion of bikeway benefits enhances the economic feasibility of paving highway shoulders.

There is much interest in North America in developing policies on the use of highway shoulders for bicycling. Also, there appears to be an interest in considering the use of shoulders for bicycling as one of the decision criteria for paving shoulders (*1*).

Paving shoulders is beneficial for a number of reasons. These include:

- Road user safety improvement because of reduced "run-off-road" and "rollover" accidents,
- Enabling the safe accommodation of bicycle travel,
- Pedestrian safety,
- Structural support of the travel lane, resulting in reduced pavement patching and maintenance cost,
- Reduced shoulder maintenance cost,
- Facilitated drainage of the roadway,
- Use of shoulder as a traffic lane during rehabilitation work,
- Enhanced snowplow operation,
- Improved highway aesthetics,
- Enabling the movement of agricultural equipment on shoulders, and
- Providing a sense of safe, open highway.

Shoulder paving criteria in North American practice have varied in many respects, but not until now has bicycle accommodation on shoulders been used as an explicit criterion for decision making.

In this paper, the bicycle use of highway shoulders is discussed and the existing policies and design practices are summarized. Partially and fully paved shoulder designs are discussed from the perspective of bicycle travel. Safety of bicycling in travel lanes and on shoulders is also covered. Because paved shoulders are a prerequisite for bicycling, the economic feasibility of paving shoulders is discussed.

RESEARCH METHODOLOGY

The research reported is part of a project on highway shoulder issues (*1*). The methodology used for the bicycle part of the overall topic consisted of: (*a*) information acquisition through a survey of provincial and state transportation departments in Canada and the United States; (*b*) study of existing practices, including policies and criteria for decision making and design; (*c*) shoulder design factors from the perspective of accommodating bicycle travel (i.e., pavement width, depth, and buffer space between motor vehicles and bicycles); (*d*) safety analysis leading to the estimation of expected accidents; and (*e*) economic feasibility of paving shoulders "without" and "with bikeways."

EXISTING PRACTICE

Existing Policies and Designs

Bicycle traffic is generally permitted on highway shoulders in Canada, with the exception of certain segments of the Trans-Canada Highway and limited access freeways (Table 1). The provinces of Alberta, British Columbia, and Manitoba appear to have the most comprehensive Canadian policies and designs regarding the use of shoulders for bicycling. Both provinces have developed policies for the accommodation of bicycle traffic under various vehicular and road characteristics. The province of Alberta, which follows the practice of fully paving shoulders, allows bicycling on designated routes that use all types of highways. A minimum of 1.1 m to the right of grooved rumble strips is provided as a bikeway on fully paved shoulders.

In Ontario, bicycles are not permitted on limited-access freeways. The definition of a provincial bikeway network is being developed in which selected highways will accommodate bicycles. Details on the width of shoulder pavements are not available. As for pavement thickness, in the absence of rumble strips, one 40-mm asphalt lift will probably be used.

In the United States, much effort is being devoted to the development of policy on bicycle use of highways and statewide bicycle planning (*2*). Survey responses indicate that there is considerable variation in policies on allowing the use of shoulders on various categories of highways for bicycling (Table 2). Bicycles are permitted on interstates and high-capacity, limited-access highways in some states, but prohibited in many states. The majority of states with policies and design criteria to accommodate bicycles use the *AASHTO Guide for the Development of Bicycle Facilities*, either in whole or in part (*3*).

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TABLE 1 Bicycle Accommodation Policies and Design in Canada

Alberta	Bicycles are accommodated on designated routes using all types of highways. A minimum of 1.1m is provided to the right of the shoulder rumble strip for bicycles. Rumble strips are used on shoulders with min. width of 2m. Indented bars are offset 150mm from the edge of the driving lane and are 750mm in length. Additional routes can be designated, if warranted, by the District Engineer.
British Columbia	Bicycles are allowed on shoulders except for Trans Canada Highway and other major highways. Travel lanes adjacent to shoulder bikeway are a minimum of 3.6m wide. Minimum design width is 2.5m for areas where highway design speed exceeds 80 kph and the SADT exceeds 10,000. For freeways and expressways, if bicycles are to be allowed, minimum width is 3.0m .
Manitoba	Design criteria require 50+ cycles per day before consideration of providing a bike path or facility. Separate bikeway facilities are provided for multi-lane highways with posted speed limits greater than 80 km/h and for two-lane highways with SADT exceeding 3000. Dimensions are 1.3m for one-way paths and 2.4m for two-way paths.
New Brunswick	No policy regarding accommodation of bicycles on highway shoulders.
Nova Scotia	Bicycles are not allowed on multi-lane, high volume highways. Consideration is given for upgrading specific routes to accommodate bicycles if Dept. of Tourism can demonstrate need and promote their use.
Ontario	Bicycles are not allowed on limited access freeways. Provincial bikeway network is to be established where selected highways will accommodate bikes. One 40mm asphalt lift will probably be used.
Prince Edward Island	No policies are in place; many bicycles use shoulders during tourist periods. Paved shoulders (2.0m) are provided on primary arterials and highways for other reasons.
Quebec	Shoulders are paved to accommodate cyclists where cycling network overlaps highway. Paved shoulders are a minimum of 1.2m wide and preferably 1.5m.
Saskatchewan	If a large number of bicycles use highways, provision of paved 3.0m shoulder is attempted.
Yukon	No policies are in place; bicycles are allowed to use paved shoulders where they exist.

Notes: 1. Information was not received from Newfoundland and Northwest Territories. 2. SADT Summer Average Annual Daily Traffic.

TABLE 2 Bicycle Accommodation Policies and Design in the United States

Alaska	No general policies; when local conditions warrant, shoulders widened to 2.4m for use as bicycle paths.
Arizona	Bicycles are permitted on all state and U.S. highways and interstates with the exception of those in urban areas. Minimum shoulder width for new construction will accommodate bicycles; policy is not established for that specific purpose.
Arkansas	Bicycles are restricted from using controlled access highways. All highway shoulders are generally paved; not specifically for bicycles.
Connecticut	Policy is under development to accommodate bicycles.
Florida	Bicycles are permitted on all free access facilities upon which at least 1.5m of paved shoulder is provided.
Idaho	Bicycles are classified as vehicles and can be used on all public roadways. Accommodation of bicycles is divided into four types and are based on the AASHTO guide for the development of bicycle facilities. Majority of rural bicycle traffic is accommodated on shoulder bikeways with a desired 1.8m width but a minimum width of 1.2m.
Illinois	Bicycles are allowed to operate on all highways except interstates. Overall policies state consideration and accommodation of bicycles in all highway projects. Specific policies are being developed based on AASHTO guidelines. Policies call for 1.2m to 1.8m paved shoulder depending on speed and ADT.
Indiana	Bicycles are prohibited on interstate highways only. Shoulders are generally paved to an 2.4m width.
Iowa	Bicycles are permitted on all highways with the exception of interstates. Shoulders are paved but not for that specific purpose.
Kansas	Bicycles are permitted on non-interstate and non-freeway highways; however the mixing of high and low speed traffic is not encouraged. The paved shoulders are not designed for bicycles.

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Survey results and literature sources indicate that the demand for the use of shoulders by bicyclists has resulted in decisions on paved shoulder widths ranging from 0.91 m to 1.83 m. Typically, shoulder bicycle lanes are about 1 m wide in each direction, separated from the remainder of the roadway by a buffer space a minimum of 0.5 m wide. The buffer area is indicated by suitable pavement marking, signs, or rumble strips. In some instances, no mention is made of a buffer area.

Shoulder Pavement Width for Bicycle Use

Factors that have influenced decisions on the width ofshoulders that should be paved for bicycle use include adjacent travel lane width, annual average daily traffic (AADT), percentage of heavy vehicle traffic, speed, bicycle traffic volume, and overall width of the shoulder. No formal methodology has been advanced for the quantification of bicyclist benefits.

TABLE 2 (*continued*)

Kentucky	Bicycles must travel away from the travel way by more than the normal shoulder width, except for urban areas with "appropriate" speed limits for motor vehicles.
Louisiana	No law or policy restricts use of paved shoulders by bicycles and no special designs are used.
Maine	Shoulders are not paved as bikeways but are paved so that bicycles can be accommodated. Policies regarding bicycles are being developed.
Maryland	Bicycle traffic is permitted on all roadways except limited access highways. To accommodate bicycles the surface course must have a hot mix asphalt course.
Massachusetts	Bicycles are prohibited on limited access highways. No additional width of shoulder beyond the AASHTO recommended width is added.
Michigan	Bicycles are prohibited from limited access highways. Usually 2.4m or normal shoulder paving is provided and a 0.9m strip is increased to 1.5m to accommodate bicycles.
Minnesota	Detailed design criteria have been established by the state DOT which incorporate ADT, through lane width and shoulder surface type and width. If the road condition is found to be "fair" or "good", then the shoulder width is deemed appropriate. Otherwise, it is improved. The guidelines also include design criteria for grades, curves and superelevation.
Missouri	A 0.9m to 1.5m bikeway is provided on the outer portion of the outside shoulder for bicycles. This area must be outside the rumble strips, if present.
Montana	On roads with a shoulder less than 1.2m the shoulder will be widened to 1.2m if there is significant bicycle traffic: a) 50 bicycles/day in 10 days/month of 3 consecutive months b) 20 bicycles/day for 3 consecutive months. Rumble strips may be deleted if heavy traffic is involved.

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SHOULDER DESIGN FACTORS

In this research, design factors that influence the cost and safety effectiveness of bikeways are of prime interest. These are the width of the paved part of the shoulder, buffer between bikeway and travel lane, and pavement depth. Other design features such as grades, curvature, and superelevation are largely controlled by the design of the highway itself and are therefore not covered in this study. Figure 1 shows shoulder designs based on the 1.5-m partially paved and 3.0-m fully paved shoulders incorporating bikeways and rumble strips.

A minimum of a 1.5-m partially paved shoulder is assumed for bicycle accommodation on low-speed highways. This width would allow the installation of rumble strips 0.5 m wide and still permit a 1-m paved surface for bicycle use. If bicycles travel close to the edge of the partially paved shoulder, a buffer area of more than

TABLE 2 (*continued*)

Nebraska	When 0.6m rumble strips are in place, bicycles are permitted to use paved shoulder of all roadways except for interstates.
Nevada	Bicycles are allowed on shoulders except for urban freeways.
New Hampshire	With the exception of interstates and turnpikes, cyclists are permitted to use paved shoulders. A few shoulders have been designed for bicycles.
New Mexico	Bicycles are allowed on all roadways except interstates. AASHTO bicycle guidelines are used and a minimum of 1.2m shoulder is provided.
North Carolina	Bicycles are permitted on all highways except for full controlled access highways. Bicycle facilities are constructed in accordance with AASHTO guidelines for bicycles. When used, rumble strips are placed in order to not present hazards to bicyclists.
North Dakota	Shoulders are not designed for bicycle traffic and their use is incidental.
Ohio	For bicycle use, shoulder width should be at least 1.2m. If vehicle speeds exceed 48km/h, if there is a high percentage of heavy vehicles or if obstructions exist on the right side, then additional shoulder width is desirable. Surfaces must be smooth and not surface treated. If rumble strips deter bicycling on the shoulder, the benefit of rumble strips is weighed against the probability that bicyclists will ride into the driving lane.
Oregon	Shoulders are commonly striped as bike lanes and are at "paved" to "full structural capacity". If highway is widened specifically for bicycles, minimal depth asphalt shoulder is used.
Pennsylvania	Policies based on AASHTO bicycle facility guide where minimum paved shoulder bike lane is 1.2m.
South Carolina	Bicycles are prohibited from freeways. Bicyclists must "ride as near to the right of roadway as practicable." Cycling is allowed on paved shoulders. Typically 0.6m partially paved shoulders are provided; 1.2m shoulders considered on a case-by-case basis.

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0.5 m would separate road traffic and bicycles. These design features for the partially paved case are intended for highways that are not in the freeway or expressway category, do not carry much traffic, and have low operating speeds. Also, it is assumed that the width of traffic lanes adjacent to shoulders are established according to design policies and that maximum speed does not exceed 90 km/hr.

To leave 1 m of the paved surface for bicycling, a total of 0.5 m is designated for both short rumble bars and the space between the edge line and rumble bars. This configuration of rumble bars was found to be practical and highly effective by the Pennsylvania Turnpike Commission. Even short, indented bars would alert errant motor vehicle drivers, as well as bicycle users, to travel within the limits of their rights-of-way on the road cross section.

For high-speed, high-volume highways with a substantial proportion of heavy vehicles, the use of fully paved shoulders is preferred.

TABLE 2 (*continued*)

South Dakota	Bicycles are restricted from interstates. With the exception of scenic or special locations, bicycle paths are usually located off the shoulder.
Tennessee	On bicycle routes, paved shoulders are used.
Utah	Use of AASHTO bicycle facility guidelines.
Vermont	Bicycles are prohibited from interstates and certain other limited access highways. State policy is to provide paved shoulders on major highways for a bicycle route system. AASHTO guidelines are used as criteria.
Washington	All highways are available for use by bicycles, except for urban freeways. Paved 1.2m shoulders are desirable.
West Virginia	Bicycles are prohibited from freeways. If allowed, safety grates are placed over inlets and rumble strips are not placed on the outside portion of the shoulder.
Wyoming	Shoulders must be 1.8m or wider in order to accommodate bicycles and rumble strip. The rumble bars have to be short enough to leave space for bicycle traffic. Pavement is at same structural strength as mainline.

Source: State DOTs.

SAFETY ANALYSIS

Safety Factors

If bicycle travel is permitted on a highway with gravel shoulders, the bicyclists are likely to use travel lanes. The difficulty that motor vehicle drivers have spotting cyclists, and the speed differential between bicycles and motor vehicles constitute risk factors (*4*). Bicycles have been noted to be the cause of collisions on rural highways. There is also the effect of motor vehicle speed on cyclists in the form of aerodynamic force (*5*) (Figure 2).

On high-speed roads with a substantial amount of heavy vehicle traffic, a cyclist's balance may be adversely affected by the air displacement caused by heavy vehicles traveling at or above posted maximum speed. If vehicle-induced aerodynamic effect is combined with strong winds, there would be an even higher risk of loss of balance.

Although detailed accident statistics of bicycle-related collisions on rural highways are not readily available, some indication can be obtained from the aggregate level accidents. According to 1991 Ontario safety data, out of a total of 396,780 motor vehicles involved in accidents, 4,347 were related to cyclists (*5*). This represents 1.09 percent of accidents. Assuming that this observation applies to highways, about 1 percent of highway accidents could be reduced if bicyclists travel on bikeways and are not hit by run-off-road motor vehicle movements.

The aerodynamic effects can be reduced to an acceptable level if sufficient buffer space is provided. For highways with up to 90 km/hr maximum speed, a 1.5 m wide (minimum) partially paved shoulder should be acceptable, provided that bicycles travel close to the edge of the partially paved shoulder. For high-speed highways with a maximum speed of 100 km/hr or higher, it would be desirable to locate the bikeway on a fully paved shoulder.

Safety Risk Analysis

The approach followed for the quantification of shoulder bikeway safety benefits calls for an estimate of reduction in expected accidents between motor vehicles and bicycles. As an example, the steps are noted in the following list for a two-lane highway case. For safety analysis of highways without bikeways on shoulders, traffic levels have to be specified. It is appropriate to use threshold AADT for economic feasibility of paved shoulder (without safety benefits attributable to cyclist safety and rumble strips) (*1*).

1. From AADT per direction, the AADT per outside lane and the corresponding hourly traffic are estimated. For the two-lane highway case, the AADT per lane is 4,000. Assuming that traffic for the design hour is 17.4 percent of AADT, the hourly traffic = 4,000 × 0.174 = 696 vehicles/hr. From volume = density × speed, using a conservative estimate of maximum speed = 100 km/hr, average density (occupancy) is 696/100 = 6.96 vehicles/km or 3.5 vehicles/0.5 km per outside lane.
2. The arrival and presence of vehicles in a representative segment of the road is estimated by the Poisson probability distribution. For risk analysis, the length of such a segment should be equal to the

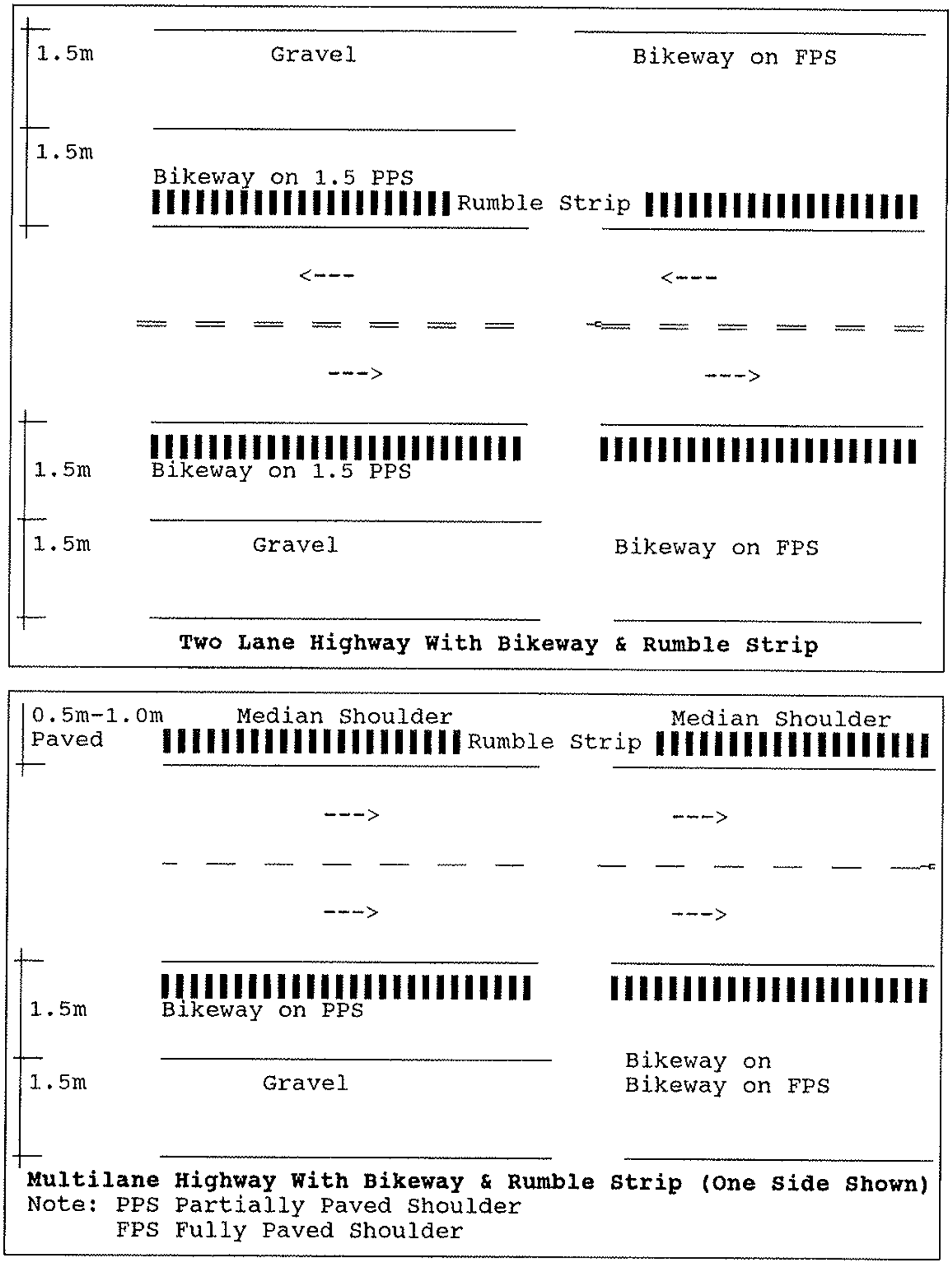
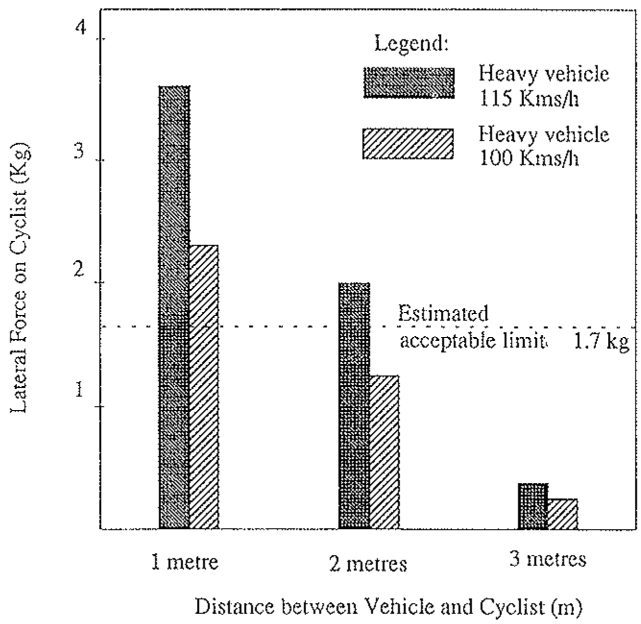


FIGURE 1 **Highway shoulder with bikeway.**

decision sight distance. For a highway with a 120 km/hr design speed, it is 470 m. For 130 km/hr, 500 m would be required to make complex or instantaneous decisions and to complete evasive maneuvers. In this case, 500 m (i.e., 0.5 km) is used. Probability of (one or more motor vehicles m/0.5 km) = $P(\text{m} > 0) = 1 - P(\text{m} = 0) = 1 - [(\text{avg.m})^0 e^{-\text{avg.m}}]/0! = 1 - [(3.5)^0 e^{-3.5}]/0! = 0.97$.

3. For 50 bicycles/day for both directions, the hourly volume = 50×0.174 = approximately 9. Using a speed of 10 km/hr, average density (occupancy) = 9/10 = 0.9/km for both directions or 0.23/0.5 km per direction. Probability of (one or more bicycles b/0.5 km per direction) = $P(\text{b} > 0) = 1 - P(\text{b} = 0) = 1 - [(\text{avg.b})^0 e^{-\text{avg.b}}]/0! = 1 - [(0.23)^0 e^{-0.23}]/0! = 0.21$.

4. The probability of a motor vehicle and a bicycle occupying 0.5-km common space on the outside travel lane is found from the joint probability: $P(\text{m} > 0).P(\text{b} > 0) = 0.97 \times 0.21 = 0.20$. The joint probabilities for common-use travel lanes are shown in Table



Source: Reference 4 (Based on an Australian Study)

FIGURE 2 Effect of motor vehicle speed on a cyclist (aerodynamic force) (*4*).

3 for a number of motor vehicular and bicycle traffic levels and facility types.

5. Considering that a run-off-road vehicle may run onto the shoulder bikeway, the joint probability of the arrival of a bicycle and a motor vehicle on the bikeway has to be found. The accident rate for "Other King's Highways" = 1.08/million vehicle kilometers. Considering that run-off-road accidents are 20 percent of total accidents, the run-off-road accident rate is = 0.2[1.08/million vehicle km] = 0.216 accidents/million vehicle km. For a representative 0.5 km of highway and for 3.5 vehicles/0.5 km per outside lane, the number of vehicles that are likely to go over shoulder = 3.5 vehicles [0.216/million vehicles] = 0.756 × 10−6 accidents for one side of highway per 0.5 km of length. From this estimate of average occupancy, the probability of a vehicle going onto shoulder = $P(m > 0) = 1 - [(0.000000756)^0 e^{-0.000000756}]/0! = 0.756 \times 10^{-6}$.

6. The probability of a motor vehicle and a bicycle occupying common space on the shoulder bikeway is found from the joint probability $P(m > 0).P(b > 0) = (0.756 \times 10^{-6}).(0.21) = 0.159 \times 10^{-6}$. See Table 3 for joint probabilities for a bikeway on the shoulder.

7. Motor vehicle-bicycle accidents per kilometer per year constitute about 1 percent of 1.08 accidents/million vehicle kilometers. For AADT per outside lane = 4,000, these are found as follows: accidents/0.5 km per year per direction = $(1.08/10^6) \times 0.01 \times 4000 \times 365 \times 0.5 = 0.008$. The preceding estimate is subject to the condition that a motor vehicle and a bicycle will jointly occupy a given part of the highway. The use of joint probabilities, presented in Table 4, is essential because a very light volume of bicycle travel is involved. For high volumes of vehicular and bicycle traffic, the joint probability would be equal to 1.0.

8. Expected accidents for AADT of 4,000/outside lane and bicycle volume of 25/day per direction = (0.008 accidents) × [$P(m > 0)$. $P(b > 0)$ of 0.2] = 0.0016/direction per 0.5 km for common use of travel lane. For a bikeway on the shoulder, expected accidents are = (0.008 accidents) × $P(m > 0).P(b > 0)$ of 0.159×10^{-6}] = 0.00127×10^{-6} accident/0.5 km per direction. Table 4 presents expected accidents per year per direction for a 0.5-km segment of highway.

ECONOMIC CRITERIA

Benefits of Shoulder Bikeway

Although there is much available literature that covers the merits and design of nonmotorized transportation (*6–9*), there is an information gap in the economic criteria for bicycle routes. This research attempts to overcome this deficiency in knowledge.

As compared with common-use travel lanes, bikeways reduce accidents (Table 4). For example, as noted in the previous section of this paper, for AADT of 4,000/direction and 25 bicycles per day per direction, 0.0016 accidents per year per direction/0.5 km are expected to result if bicycles share the roadway with motor vehicles. On the other hand, a negligible number of accidents are expected to occur for a paved bikeway on shoulder. Therefore, 0.0016 accidents per 0.5 km/year per direction can be saved by shoulder bikeways. For both directions, accident reduction amounts to 0.0032/0.5 km or 0.0064/km.

The economic value of preventing an accident is estimated from recently updated cost information reported by the Ministry of Transportation, Ontario (*10*). The total social cost per crash includes direct costs and indirect costs. The direct costs cover property damage (i.e., vehicle and contents, transportation infrastructure damage, buildings and other property damage, and environmental damage) and time and material consumed (i.e., police, fire, ambulance, tow trucks, hospital emergency, hospital ward, other medical, rehabilitation, out-of-pocket expenses, and insurance administration). The indirect costs, estimated through the willingness-to-pay approach, cover value of human life.

From the cost of accident information and Ontario highway safety data on the proportion of various accidents (i.e., fatal, personal injury, or property damage), the value of saving one accident is found to be $76,638.84 (1994 Canadian dollars) (*1*). According to FHWA methodology reported by Cottrell (*11*), the value of preventing an accident is $75,982.90 (1994 Canadian dollars).

The benefits of bikeway = 0.0064 accidents/km per year × $76,638.84 = $490.48/km per year (1994 Canadian dollars) (for both sides of travel). For a 6 percent interest rate (real) and a 12-year life of shoulder pavement, the present worth of benefits = $4,112. These dollar benefits are added to other benefits per kilometer per year, in economic feasibility analyses (i.e., expressed in present worth, $1,503.23 for maintenance cost reduction, $51,709.23 for safety without rumble bars, $8,100.50 for safety of rumble bars). See Table 5 for cost information.

Economic Feasibility

Economic feasibility of partially or fully paved shoulders can be investigated by comparing benefits and costs of shoulder pavement. To begin with, road user safety benefits and reduction of maintenance expenditure are the only benefits that are included in the feasibility analysis. Table 5 presents results in terms of AADT threshold values for economic feasibility of shoulder pavements of two-lane and multilane highways (excluding freeways). In a number

TABLE 3 Probability of a Bicycle and a Motor Vehicle Occupying Common Space

AADT Motor Veh/ Direction	Bicycles/ Day/Dir.	Outside Lane/ Shoulder Traffic	P(m>0)	P(b>0)	P(m>0 x P(b>0)
Two Lane Highway					
Common Use Travel Lanes					
4000	25	4000 veh 25 bikes	0.97	0.21	0.20
4500	25	4500 veh 25 bikes	0.98	0.21	0.21
Bikeway on Shoulder					
4000	25	4000 veh 25 bikes	0.756×10^{-6}	0.21	0.159×10^{-6}
4500	25	4500 veh 25 bikes	0.842×10^{-6}	0.21	0.177×10^{-6}
Four Lane (Undivided)					
Common Use Travel Lanes					
4000	25	2000 veh 25 bikes	0.82	0.21	0.17
4500	25	2250 veh 25 bikes	0.86	0.21	0.18
Bikeway on Shoulder					
4000	25	2000 veh 25 bikes	0.376×10^{-6}	0.21	0.079×10^{-6}
4500	25	2250 veh 25 bikes	0.423×10^{-6}	0.21	0.089×10^{-6}
Multilane (Divided)					
Common Use Travel Lanes					
8000	25	4000 veh 25 bikes	0.97	0.21	0.20
9000	25	4500 veh 25 bikes	0.98	0.21	0.21
Bikeway on Shoulder					
8000	25	4000 veh 25 bikes	0.756×10^{-6}	0.21	0.159×10^{-6}
9000	25	4500 veh 25 bikes	0.842×10^{-6}	0.21	0.177×10^{-6}

Notes: (1) P(m>0) Probability of the presence of one or more vehicles/0.5 km. (2) P(b>0) Probability of the presence of one or more bicycles/0.5 km. (3) The probability of the presence of a motor vehicle as well a bicycle (together). (4) The presence of a motor vehicle on shoulder implies a run-off-road movement. (5) Bikeway on Shoulder is assumed to be paved of at least 1.0m width per direction.

of cases, because the nearest thousand was used as the threshold AADT level, the benefit-cost ratio is greater than one.

The sensitivity of the benefit-cost ratio to AADT levels for various shoulder pavement widths was investigated. Because both the benefits and the cost of paving shoulders increase with increasing pavement width, the threshold AADT levels for various pavement widths do not change appreciably. Although the focus of this paper is not on rumble strips, it is relevant to note that the addition of rumble strip improves the benefit-cost ratios considerably because their benefits are much higher than their costs.

In the case of a bikeway, there is no additional cost involved. On the other hand, the provision of a bikeway contributes safety benefits. Therefore, the addition of bikeway benefits improves the economic feasibility of paved shoulders (Table 5).

CONCLUSIONS

1. Although there is a growing trend toward accommodating bicycles on highway shoulders, there is no consensus on the width of pavement or the need for a buffer area between vehicular traffic and the bikeway.

2. Allowing bicycle use on travel lanes of a highway with gravel shoulders exposes road users and bicyclists to risk of accidents. For

TABLE 4 Expected Accidents Between a Motor Vehicle and a Bicycle Over a 500-m Section

AADT (Motor Vehicle)/ Direction	Bicycles/ Day/ Direction	Joint Prob. P(m>0).P(b>0) (Each Dir.)	Vehicle-Bicycle Acc./0.5Km/Year (Each Dir.)	E(Acc./ 0.5Km/Year) (Each Dir.)
Two Lane Highway				
Common Use Travel Lanes				
4000	25	0.20	0.0080	0.00160
4500	25	0.21	0 0088	0.00185
Bikeway on Shoulder				
4000	25	0.159×10^{-6}	0.0080	0.00127×10^{-6}
4500	25	0.177×10^{-6}	0.0088	0.00156×10^{-6}
Four Lane Undivided				
Common Use Travel Lanes				
4000	25	0.17	0.0040	0.00068
4500	25	0.18	0 0044	0.00079
Bikeway on Shoulder				
4000	25	0.079×10^{-6}	0.0040	0.00032×10^{-6}
4500	25	0.089×10^{-6}	0.0044	0.00039×10^{-6}
Multilane Divided				
Common Use Travel Lanes				
8000	25	0.20	0.0080	0.00160
9000	25	0.21	0 0088	0.00185
Bikeway on Shoulder				
8000	25	0.159×10^{-6}	0.0080	0.00127×10^{-6}
9000	25	0.177×10^{-6}	0.0088	0.00156×10^{-6}

Notes: (1) P(m>0).P(b>0) Joint probability of the presence of a motor vehicle as well a bicycle (together). (2) The presence of a motor vehicle on shoulder implies a run-off-road movement. (3) Vehicle-bicycle accident rate is assumed to be 1% of the total accident rate for the highway. (4) The Motor Vehicle-Bicycle Accidents/0.5 km/Year assume the presence of both a vehicle and a bicycle with a probability of 1.0. (5) E(Acc./0.5 km/Year) Expected accidents = Accidents x Joint Probability. (6) Bikeway on Shoulder is assumed to have 1.0m (min) width per direction.

instance, for a two-lane highway with an AADT of 8,000 or for a multilane divided highway with an AADT of 16,000, if bicycle traffic per day amounts to 50, the expected accident rate is 0.032/0.5 km per year. Even if the use of travel lane is forbidden, the difficulty of bicycling on soft gravel shoulders is likely to result in joint use of travel lanes by motor vehicles and cyclists.

3. Compared with common-use travel lanes, shoulder bikeways reduce accidents. For example, for AADT of 8,000 and 50 bicycles per day, the expected bicycle-related accident rate is negligible (i.e., 0.00254×10^{-6}/0.5 km).

4. The bicycle safety benefits of paved shoulders enhance the overall economic feasibility of paving shoulders. The threshold AADT for feasibility would drop if bicycle safety benefits are included in economic feasibility analyses.

5. The bikeway benefits, as well as rumble strip benefits, are a function of vehicular and bicycle traffic and the economic value of preventing an accident. These do not vary with shoulder pavement width. On the other hand, the combined maintenance and motor vehicle user safety benefits increase linearly with an increase in shoulder pavement width. Because there is a high proportion of motor vehicle user benefits within total benefits (i.e., that would accrue as a result of paving shoulders, installing rumble strips, and allowing a bike route to operate on paved shoulder), total benefits increase with shoulder pavement width. Because capital cost and benefits rise at nearly the same rate, the threshold levels of AADT for various shoulder pavement widths do not differ markedly.

6. Rumble strips are cost-effective for reducing run-off-road accidents and also serve as a buffer between a travel lane and a bicycle route.

7. On low-speed highways (maximum posted speed < 100 km/hr), a 1.5-m (minimum) shoulder pavement width would be sufficient for the provision of a cycle lane, as well as the placement of rumble bars. Pavements for such indented rumble bars, as well as bikeways, should preferably be a minimum of 80 mm asphalt concrete.

8. For high-speed, high-volume highways, the buffer area between motor vehicles and bicycles has to be increased because of the high aerodynamic effect of heavy vehicles on cyclists. In such a case, fully paved shoulders would be desirable.

TABLE 5 Economic Feasibility of Paving Highway Shoulders with a Bicycle Track and Rumble Strips (1991 Canadian Dollars)

	Two Lane	Four Lane Undivided	Multilane With Median
Shoulder Pavement 1.5m on Both Sides			NA
Without Rumble Bars & Without Bicycle Track			
AADT Threshold (2 Sides)	8000	8000	
Cost	$54,144	$54,144	
Benefit/Cost Ratio	Appr.1.0	Appr.1.0	
With Rumble Bars & Without Bicycle Track @AADT = 8000 (2 sides)			
Cost	$56,050	$56,050	
Benefit/Cost Ratio	1.09	1.09	
With Rumble Bars & With Bicycle Track @AADT = 8000 (2 Sides) & 50 Bicycles/Day (2 Sides)			
Cost	$56,050	$56,050	
Benefit/Cost Ratio	1.17	1.13	
1.5m Outside, 0.5m Median	NA	NA	
Without Rumble Bars & Without Bicycle Track			
AADT Threshold (2 Sides)			16000
Cost/Km			$72,192
Benefit/Cost Ratio			Appr.1.0
With Rumble Bars & Without Bicycle Track @AADT = 16000 (2 Sides)			
Cost/Km			$76,004
Benefit/Cost Ratio			1.15
With Rumble Bars & With Bicycle Track @AADT = 16000 (2 Sides) & 50 Bicycles/Day (2 Sides)			
Cost/Km			$76,004
Benefit/Cost Ratio			1.20
Shoulder Pavement 3.0m on Both Sides			
Without Rumble Bars & Without Bicycle Track			
AADT Threshold (2 Sides)	9000	9000	
Cost/Km	$108,288	$108,288	
Benefit/Cost Ratio	1.07	1.06	
With Rumble Bars & Without Bicycle Track @AADT = 9000 (2 Sides)			
Cost/Km	$110,196	$110,196	
Benefit/Cost Ratio	1.13	1.12	

(continued on next page)

TABLE 5 (*continued*)

Shoulder Pavement	Two Lane	Four Lane Undivided	Multilane With Median
3.0m on Both Sides			NA
With Rumble Bars & With Bicycle Track @AADT = 9000 (2 Sides) & 50 Bicycles/Day			
Cost/Km	$110,196	$110,196	
Benefit/Cost Ratio	1.17	1.14	
3.0m Outside, 1.0m Median	NA	NA	
Without Rumble Bars & Without Bicycle Track			
AADT Threshold (2 Sides)			18000
Cost/Km			$144,384
Benefit/Cost Ratio			1.05
With Rumble Bars & Without Bicycle Track @AADT = 18000 (2 Sides)			
Cost/Km			$148,196
Benefit/Cost Ratio			1.15
With Rumble Bars & With Bicycle Track @AADT = 18000 (2 Sides) & 50 Bicycles/Day (2 Sides)			
Cost/Km			$148,196
Benefit/Cost Ratio			1.18

Notes: (1) Shoulder pavements for two lane, 4 lane undivided and multilane highways (other than freeways) are 80mm depth (two lifts) and life is 12 years. (2) Interest rate is 6% (real). (3) NA Not applicable.

9. Bikeways should be designated only on the outside shoulders of multilane highways. Bicycling should not be allowed on median shoulders.

ACKNOWLEDGMENT

This paper is based on a study sponsored by the Ministry of Transportation, Ontario, Canada. Opinions expressed are those of the authors.

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DISCUSSION

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The authors have presented an intriguing paper that covers a vital and timely subject. They are to be commended for initiating an effort to consider bicycle usage and safety part of a warrant for the installation of shoulders on highways. I have comments regarding the authors' methodology and conclusions.

The authors have developed a probabilistic basis in an effort to assess the accident exposure of bicyclists. I do not agree with the authors' assumptions or their approach. For example, the authors have defined the conflict frequency as the joint probability of a bicyclist and vehicle occupying the same space. I do not agree that this approach is reasonable because there is such a large speed discrepancy between the vehicles. However, if one accepts their approach, such an approach should be self-consistent.

The joint occupancy of a bicycle and a motor vehicle within a given road segment has been used as a basis for risk analysis. The length of the road segment has been used as the decision sight distance. The authors have chosen to use the decision sight distance for a motor vehicle speed of 130 km/hr (approximately 80 mph), which is excessive. The authors should use the decision sight distance that corresponds to the average speed of the cars on the type of road to which the paper applies. The risk analysis developed by the authors applies to two-lane rural highways with speeds of up to 90 km/hr (approximately 55 mph). The decision sight distance for that speed (250 m) should be used instead of the much greater distance for the higher speed chosen by the authors.

The bicyclist travel speed chosen for the risk analysis is much too slow. The use of extreme values is improper; average speeds should be used for both the bicyclist and the motorist. The average travel speed for the bicyclist should be 25 km/hr for the risk analysis.

The use of shoulders reduces the likelihood of overtaking accidents only. The risk analysis should use the fraction of this type of automobile-bicycle accident rather than all bicycle accidents. This was about 10 percent in a study by Kenneth Cross (*1*).

The foregoing objections to the authors' methodology would reduce the bicyclist accident risk. However, a bicyclist involved in a rural highway overtaking accident is much more likely to suffer extremely serious injuries or death. In the Cross study (*1*), 38 percent of the fatal accidents were of the motorist overtaking type. As a result, the cost of such an accident would be much higher than the cost of an average automobile accident chosen by the authors. The estimated cost for a death is $410,000 (U.S. dollars) (*2*). Because these factors are compensating, I believe that the estimated safety benefit of shoulders derived by the authors of $490/km is acceptable.

I believe that the use of a "real" interest rate to discount future costs to present value is not appropriate. When medical costs are growing faster than all costs (i.e., the inflation rate exceeds the discount rate), then the "real" interest rate of future costs in a present worth calculation would be negative. In other words, the present value of each future annual cost is greater that the present cost. In such cases, I would use a discount rate equal to the inflation rate. For these cases, to determine the present value of future expenditures, the present value is multiplied by the number of years in the period. In the present paper, I believe the present worth of the annualized safety benefit of shoulders for bicyclists should be at least $5,900/km.

The authors have presented the cost-benefit analysis of highway shoulders for bicyclists in Table 5. I disagree with the authors' assumptions in developing the cost-benefit analyses. The authors have chosen to bar bicyclists from the paved shoulder unless it is designated as a bicycle path. Therefore, the safety benefits of the presence of the paved shoulder for bicyclists have not been included. However, the presence of a paved shoulder makes it a bicycle path regardless of designation; therefore, the safety benefits of the shoulder accrue to bicyclists and should properly be included in the cost-benefit analysis.

When rumble strips are present on a paved shoulder without a bicycle track, then bicyclists will be effectively barred from the shoulder and will continue to travel in the vehicle lane. The safety threat to bicyclists must be considered as a cost in this case. The authors have not included this as a cost in their analysis.

When a paved shoulder is present with both rumble strips and a smooth bicycle track of adequate width, then the safety benefit to bicyclists can properly be included as the authors have done. As an experienced commuting and touring bicyclist, I strongly believe that the 1.0-m bicycle track width proposed by the authors is not sufficient. The AASHTO guide for bicycle facilities recommends a minimum width of 1.5 m (5.0 ft) for a bike lane (*3*). I believe that the bicycle path on the shoulder should be at least 1.5 m wide. When 0.5 m wide rumble strips are used as proposed by the authors, the total width of shoulder with bicycle path should be 2.0 m. The cost of the shoulder must be increased accordingly.

I have modified the two-lane portion of the authors' Table 5 to include these cost adjustments; the data are presented as Table 6.

Based on my adjusted economic feasibility analysis, the authors' conclusion that paved shoulders with rumble strips have a favorable benefit-cost ratio for bicyclists is dubious. Using the authors' analysis with my modifications, smooth-paved shoulders are clearly more favorable than shoulders with rumble strips. The additional benefit to motorists of rumble strips is more than negated by costs to bicyclists. Thus, installation of rumble strips does not result in a favorable benefit-cost ratio.

TABLE 6 Economic Feasibility of Paving Highway Shoulders on Two-Lane Highways as a Benefit to Bicyclists

A) 1.5 m Smooth-Paved Shoulders Both Sides:
AADT 8,000
Bikes 50
Cost/km $54,100
Benefit $59,100
B/C ratio 1.09

B) 1.5 m Paved Shoulders With Rumble Strips Both Sides, no Bicycle Track:
AADT 8,000
Bikes 50
Cost/km $62,000
Benefit $61,300
B/C ratio 0.99

C) 2.0 m Paved Shoulders With Rumble Strips and 1.5 m Bicycle Track Both Sides:
AADT 8,000
Bikes 50
Cost/km $74,100
Benefit $67,200
B/C ratio 0.91

D) 3.5 m Traveled Lane With 0.5 m Rumble Strips and 1.5 m Smooth-Paved Shoulders Both Sides:
AADT 8,000
Bikes 50
Cost/km $56,100
Benefit $67,200
B/C ratio 1.20

At the travel threshold assumed by the authors, rumble strips do not show a favorable benefit-cost ratio. Rumble strips can be installed within the right-hand portion of both of the motor vehicle travel lanes so that an adequately wide, smooth-paved bicycle track is provided. This design option yields the benefit of the adequate path on the shoulder for bicyclists and the benefit of the rumble strips for motorists. The favorable benefit-cost ratio for this design option is shown in Option D of Table 6. If rumble strips are to be used, they should be installed at the edge of the automobile travel lane, not in the shoulder.

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AUTHORS' CLOSURE

We appreciate the comments received, although we disagree with most points raised by the discussant. Furthermore, we cannot endorse views expressed by the discussant.

1. The discussant states that he does not agree with our assumptions or our approach. Although he has provided different assumptions in some instances, he does not suggest an alternative approach.

2. The risk analysis methodology we developed can be applied to any highway type. A two-lane highway case is used to illustrate details of the methodology. The methodology is not limited to two-lane highways with speeds of up to 90 km/hr (approximately 55 mph). The rural arterial highways in Canada are designed for a range of 80 to 130 km/hr. See Table A.5a of Reference 1. Two-lane highways with high geometric design standards are used for long distance journeys. On these highways, drivers frequently travel close to design speed. Therefore, a decision sight distance of 500 m is used in risk analysis.

3. A 10 km/hr sustained speed of bicyclists is consistent with the 8 to 12 km/hr range suggested in the literature (*2*). In the case of bicycle tracks that are not on highway shoulders, a design speed of 20 to 30 km/hr is used for establishing radius of curvature, superelevation, and other geometric design features, because such tracks are used for short bicycling trips (*3*). It is doubtful whether bicyclists can maintain sustained speeds higher than 10 km/hr on long distance rural routes. For this type of travel, the bicyclists normally have to transport heavy backpacks, etc., which contributes to slower speeds.

4. The issues raised by the discussant in Item 5 of his discussion are already addressed by our methodology. Details are presented in the Safety Risk Analysis section of the paper.

5. We believe that our estimates of bicycle-related accidents, as well as cost of accidents, are valid.

6. We use a "real" interest rate for discounting future benefits expressed in constant (i.e., real) dollars. The cost of constructing shoulder pavements is presented in present worth terms, therefore no discounting is involved. The purpose of economic analysis in real dollar terms is to work with cash flows adjusted for inflation. If the rate of interest is set equal to inflation (applicable to highway transportation), it amounts to setting the real rate of interest equal to zero. Therefore, the future benefits are not discounted and the benefit-cost ratio tends to favor investments that may not be feasible according to the private sector practices. Therefore, caution should be exercised in setting the real rate of return equal to zero. Further information on this subject can be found in Chapter 13 of Reference 4.

7. The discussant states that "the authors have chosen to bar bicyclists from the paved shoulder unless it is designated as a bicycle path." The fact that bicyclists' benefits are included in the various tables should suggest that the discussant has misunderstood the intent of economic analyses, which show cost-benefit results "without" and "with bicyclists' " benefits. If the bicyclists are permitted by highway authorities to use a given highway and if a paved or a partially paved shoulder is available, it is logical that bicyclists are expected to travel on the shoulder pavement.

8. The discussant states that "when rumble strips are present on a paved shoulder without a bicycle track, then bicyclists will be effectively barred from the shoulder and will continue to travel in the vehicle lane." As noted in Item 7, if bicyclists are allowed to use the highway right-of-way and if a paved or a partially paved shoulder is available, the bicyclists are expected to travel on the shoulder.

9. For one-way travel, a minimum shoulder pavement width of 1 m is adequate and sustainable. It is of course assumed that the bicyclist is not using a trailer. The survey results and literature sources reported in the paper indicate that the demand for the use of shoulders by bicyclists has resulted in decisions that range from 0.91-m to 1.83-m paved shoulders. Given that the "essential space" for a bicyclist is 1 m per direction, it is not surprising that typically bicycle lanes on Highway 4 shoulders are about 1 m per direction and are separated from the remainder of the roadway by a buffer space of 0.5 m (minimum). The treatment of the buffer area differs from agency to agency. These include suitable pavement marking, signs, and rumble strips. It should be noted that lane edge marking and rumble strips of 0.5 m do not interfere with the 1-m "essential space" for cycling. According to survey returns, in some instances no mention is made of a buffer area.

10. The authors do not agree with the discussant's logic or his computations of the benefit-cost ratios.

11. Contrary to the discussant's view, the rumble strips improve the economic feasibility of the shoulder pavements (Table 5). The benefits of installing rumble strips exceed their cost. For example, in the case of a two-lane highway with a 1.5-m partially paved shoulder, the cost of rumble strips per kilometer is $1,906 and benefits per kilometer is $5,045. This gives a benefit-cost ratio of 2.65. Given this information, it is surprising that the discussant states that "at the travel threshold assumed by the authors, rumble strips do not show a favorable benefit-to-cost ratio."

12. We cannot endorse the view of the discussant that rumble strips can be installed within the travel lanes. This action would cause an increase in accidents because the width of travel lanes would be reduced from 3.66 m (12 ft) to 3.16 m (10.4 ft). According to the FHWA (*5*), for a rural two-lane highway on flat terrain with a 1.524-m (5-ft) shoulder pavement and another 1.524-m (5-ft) unpaved shoulder; an average roadside hazard index of three out of seven; a side slope of 7:1; and a recovery distance of 9.15 m (30 ft), reducing the travel lane from 3.66 m (12 ft) to 3.05 m (10 ft) would cause a 29 percent increase in related accidents. If the lane width is reduced from 3.66 m (12 ft) to 3.35 m (11 ft), it would result in a 13 percent increase in related accidents. On the other hand, by providing a minimum 1-m shoulder pavement for use by bicyclists, plus a rumble strip of 0.5 m as a buffer area, the safety of bicyclists as well as motorists would be enhanced. In the case of jurisdictions in which it is considered desirable to provide wider shoulder pavements for use by bicyclists, the threshold levels of AADT are noted in the paper.

Publication of this paper sponsored by the Committee on Bicycling and Bicycle Facilities.