

Observational Assessment of the Effectiveness of Traffic Control Devices on Lane Use Compliance on Motorways

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1 **ABSTRACT**

2 Modern roadway design philosophy assumes that slower and non-continuing vehicles remain in the
3 outside lanes of motorways, which are median-divided, multi-lane, high-speed free-flow roads
4 characterized by controlled and limited access, e.g., freeways. Correspondingly, proper selection of a
5 travel lane by the vehicle operator is generally understood to enhance safety and operational performance.

6 Lane selection according to the *basic rule* assumes that the innermost (median-adjacent) lane of
7 the roadway in each direction functions as an auxiliary lane, being reserved for vehicles expediting
8 passing maneuvers and subsequently vacating the lane. Cultural perspectives indicate a conflict between
9 those who value the flexibility of passing lane availability and others who demand strict compliance with
10 the speed limit, constraining the availability of this auxiliary lane. Such inflexible adherence to speed
11 limits by vehicle automation systems and Intelligent Speed Assistance will further exacerbate the
12 prevalence of antisocial inappropriate lane use.

13 This paper presents a model developed to identify the position (*leftward, rightward*) and status
14 (*expediting, blocking, cruising*) of vehicles using the inside lane, based on time-space relationships.
15 Application of this discrete model to a heuristic field investigation of basic rule conformance and
16 responsiveness indicated limited local and systemic effectiveness of regulatory signing in the United
17 States. Cruising and blocking behaviors were observed to be commonplace, suggesting imbalanced
18 enforcement with respect to speed and a need for additional auxiliary lanes along uphill grades and within
19 interchanges. Alongside adjustments to policy, enforcement, and education, tactical deployments of
20 active-feedback signing hold potential for improving conformance with the basic rule.

21

1 TREATISE

2 In the early 20th century, concomitant with an increase in vehicle capabilities at higher speeds,
3 transportation engineers began to design high-speed roadways that featured separation of traffic
4 movements. Roadways such as the Autobahn in Europe and the Pennsylvania Turnpike in North America
5 were designed for free-flowing motorized traffic, allowing for unlimited speeds on account of what can be
6 described as the basic rule. The basic rule is imbued in modern design philosophy, a means of promoting
7 courtesy and order. It governs the use of the innermost lane – the left lane in left-hand-drive countries –
8 requiring users to keep right unless actively passing another vehicle, such that any vehicle in the left lane
9 must yield the left lane to all faster traffic.

10 The basic rule thereby also requires that heavy vehicles and slower vehicles will also typically
11 keep right and are often restricted to the right lane or lanes for the purposes of improving operations.
12 Traffic operations engineers thus often seek to limit passing activity that would inhibit the on-demand use
13 of the left lane by faster vehicles while planning and implementing projects that improve motorway
14 capacity and safety to support the broadest possible applicability of the basic rule, which is not
15 consistently applied where inadequate capacity exists or where safety risks are identified.

16 Of interest to many in the transportation field is the notion that the basic rule itself is ubiquitous
17 and often signed in pedestrian, bicycle, and mixed-use applications. At airports with moving walkways,
18 patrons are asked to stand to the right and walk on the left with a combination of signing and word
19 messages incorporated into the treads of the moving walkway itself. On shared-use paths, people walking
20 are expected to keep to the right to allow faster users, such as people bicycling, to pass on the left. From
21 an early age, in the classroom and the lunch line, children learn that standing to the right and yielding the
22 left side of the body to moving and faster people is commonplace. This lesson inferred from the simple
23 observation of movement and occasionally enforced with the voice of a kindergarten teacher, is a
24 reminder of the basic courtesy that is offered to all.

25 Because the intent of the left lane under free-flow conditions is that it serves a transient purpose,
26 the left lane is considered an auxiliary lane, even as it is typically continuous. Motorway design standards
27 in Europe, the Middle East, and Southeast Asia allow for a left shoulder width that is narrower than what
28 is called for in the publication *A Policy on the Geometric Design of Highways and Streets*, a design
29 resource used in the United States of America referred to as the “*Green Book*”, published by the
30 American Association of State Highway and Transportation Officials. The *Green Book* itself describes
31 auxiliary lanes, including deceleration, acceleration, and part-time use lanes. The latter application is the
32 purpose of the left-most lane on the vast majority of rural motorways and rural multi-lane divided
33 highways with motorway characteristics. The exception to the transient availability of the left lane occurs
34 when flow regimes exceed the capacity of the right lane, a function of demand, the composition of the
35 traffic stream, and environmental conditions.

36 Such free-flowing roads (“freeways”) are designed for motor vehicles (“motorways”), providing
37 an express route compared to conventional roads (“expressways”), incurring dramatic benefits in terms of
38 time, comparative safety performance, fuel economy, and emissions reductions, particularly when
39 compared to economic productivity. The distinct advantage of a motorway lies in its provisions for the
40 separation of traffic. Grade separations are used to remove conflicts between the motorway and

1 intersecting roadways, separating crossing traffic. Roadway geometry is used at junctions to provide for
2 decelerating and accelerating traffic, separating maneuvering traffic from continuing traffic. Continuing
3 traffic itself is also likewise separated by the basic rule through stratification, without the need for barriers
4 or bridges.

5 Even without accommodations for separating traffic, the horizontal and vertical alignment of a
6 four-lane rural free-flow road often incurs higher speeds in tangent segments and through sag vertical
7 curves. Correspondingly, differing energy demand profiles in various segments illustrate the need for
8 speed-based stratification of vehicles of contrasting power delivery capabilities. The effects of inferred
9 design speed^a must therefore be considered irrespective of the provision of access, given that roadway
10 alignment influences driver selection of speed, along with roadside design.

11 Stratification of vehicles among the lanes of the motorway as a result of slower-moving vehicles
12 occurs in concert with the harmonization of vehicle and vehicle operator capabilities. Reserving the left
13 lane of the motorway for transient operations by the most flexible and capable vehicles preserves order in
14 operations on the motorway, one of the primary goals of a motorway operations engineer. Promoting
15 order in high-risk environments is a means of achieving optimal safety performance. Stratification
16 according to contrasting vehicle speeds and vehicle capabilities is a function of user action. Users
17 perform the task of choosing a lane in order to maintain occupancy of the appropriate lane. This practice
18 is colloquially referred to as lane discipline and is distinct from lane use control, which is implemented
19 most often with regulatory signs, but sometimes supplemented with markings or signals, indicating the
20 use of lanes for intended turning movements or restrictions on vehicle types and activities.

21 Taken together, the action of lane discipline based on lane use control can be considered lane use
22 compliance, the topic of this paper. Lane use compliance, being a function of the user and the vehicle, is
23 also influenced by the actions of other users, particularly with regard to vehicle posture and vehicle
24 indications, including the headlights, a common practice in Europe.

25 This paper presents the results of field observations, a sign inventory, a practice-based model for
26 passing activity, and recommendations related to further analysis and safety-driven countermeasures. A
27 recommendation for follow-on research activities includes suggestions for revisions to existing signing
28 and marking applications, changes to policies, and proposed practices that can enhance the performance
29 of at-risk motorway segments and corridors.

^a The concept of inferred design speed was popularized in pioneering research led by practitioners including RJ Porter. Motorways and rural highways typically feature generous horizontal and vertical curves, an indication to vehicle operators that the road will safely support speeds much higher than the actual design speed, which typically controls the minimum values for various geometric design features.

1 INTRODUCTION

2 Motorway operators worldwide use a variety of traffic signing and lane markings to convey messages to
3 road users regarding the anticipated, appropriate, proper, and, as required, lawful, use of various lanes on
4 roadways. On arterial roads approaching intersections, signing and markings indicate lane use control, or
5 restrictions on the use of lanes. Similarly, on motorways, arrows, letters, and symbols are used to convey
6 guidance and regulatory information in advance of interchanges and along segments. Restricted-use
7 lanes, such as those dedicated to use by high-occupancy vehicles, are often continuously marked and
8 signed at intervals as little as 500 meters (approximately 1500 feet), often accompanied by pavement
9 marking symbols such as a passenger bus outline or a diamond.

10 Lanes not intended for use by continuing traffic are considered auxiliary lanes, with a variety of
11 applications being described in the AASHTO “*Green Book*”. The anticipated use of auxiliary lanes is not
12 merely to be inferred but is often an intended outcome of roadway geometric design for both intersection
13 auxiliary lanes and continuous auxiliary lanes. In addition to geometric design cues such as taper rates
14 and curb type, signing and markings apply to auxiliary lanes.

15 Intersection auxiliary lanes are typically dedicated to turning movements or, in some cases,
16 passing of transient left-turning vehicles occupying the through lane. Located on intersection approaches
17 and departures, the lengths of these auxiliary lanes for turning movements are typically determined by the
18 expected queue length or required distance for vehicle velocity changes. Continuous auxiliary lanes are
19 located along roadway segments and include lanes dedicated to various uses such as continuous right
20 turns, mass transit vehicles, trucks when climbing vertical grades, part-time shoulder use, and, by custom
21 and code in many places, continuing and unrestricted lanes dedicated to vehicles passing using the
22 innermost lane.

23 Research Theory and Hypothesis

24 The impetus for this research activity is a growing concern regarding the safety performance of at-risk
25 motorway segments. Such at-risk segments exhibit some degree of degradation in operations and
26 marginal scores for surrogate safety measures, such as following distance. Often, this degradation in
27 safety is evident in the failure to apply and enforce the *basic rule*. (The basic rule is described in the
28 treatise that begins this paper, on pages 1 and 2.)

29 While certain operational effects can be readily corrected through spot capacity improvements,
30 such as auxiliary lanes, these improvements may have limited effect if the basic rule is not inured and
31 compliance enforced such that adherence to the basic rule is ubiquitous.

32 Identifying, characterizing, and assessing compliance with the basic rule will aid motorway traffic
33 operations engineers with designing and implementing traffic control devices that induce compliance and
34 aid enforcement of the basic rule, thereby protecting the liberty of travelers on the motorway with respect
35 to vehicle and operator capabilities and limitations. In essence, such an approach to roadway operations
36 respects human factors science, particularly with respect to behavioral analysis.

37

1 The working theory of this research activity is described in three parts, each of which describes
 2 characteristics of the basic rule, that is, that slower and heavier vehicles will remain to the right on
 3 motorway segments and that all vehicles will minimize time spent in the left lane by expediting passing
 4 maneuvers. Three theories regarding the basic rule are listed below.

- 5 1. **Basic rule compliance improves operations**, both in terms of safety performance and a
 6 reduction in behaviors with higher risk factors. Such behavior includes, but is not limited
 7 to, following too closely, sudden and erratic lane changes, and driving practices that may
 8 be associated with social-behavioral disorders, such as consistently denying other vehicle
 9 operators the use of a lane or repeatedly wantonly violating a signal indication.
- 10 2. **Basic rule compliance can be measured according to a space-time relationship**
 11 analysis of vehicles in the flow of traffic, such that violations of the basic rule are
 12 mathematically represented through conventional safety-based driving behavior and
 13 human factors analysis and, correspondingly, a means of improving the Level of Service.
- 14 3. **Basic rule compliance is an act of courtesy, influenced by statute, training, traffic**
 15 **control devices, enforcement campaigns, and the behavior of other drivers** with
 16 respect to vehicle posture; attention to basic rule compliance is a philosophical approach
 17 to motorway operations that values order and flexibility for the most capable users.

18 Based on this theory, a two-part hypothesis was used to provide a framework for evaluating the
 19 effectiveness of traffic signing related to use of the left lane on motorways.

20 Hypothesis 1 states “The approximate time-to-complete for a passing activity is a primary and
 21 **independent indicator of the disruption incurred by other vehicles intending to use the left lane** and
 22 can be related to the instantaneous observed Level of Service (an indication of the ability of vehicle
 23 operators to change lanes) by vehicles whose operators are not achieving the desired speed.”

24 Hypothesis 2 states “Accounting for variances associated with geography, fraction of heavy
 25 vehicles, and the observed Level of Service in a segment, **it is common that vehicles will be inhibiting**
 26 **the flow of traffic in the left lane.**”

27 Examination of these hypotheses is undertaken with an examination of vehicle state with respect
 28 to time. This examination considers the position of interacting vehicles and the change in position, which
 29 occurs as a result of speed changes, also resulting in changes in headways.

30 **Description of Vehicle States**

31 Contemporary literature does not appear to address a description of various vehicle states with regard to
 32 passing maneuvers. The vehicle states proposed in this research relate vehicle position to a space-time
 33 diagram, with the goal of measuring left lane occupancy in terms of *total time to pass*. Vehicle position
 34 can be characterized by lane selection, by relative position to other vehicles, and by the vehicle’s impact
 35 on other vehicles.

36 Vehicles in the mixed flow of traffic include continuing and non-continuing vehicles. Vehicles
 37 remaining out of the left lane are *rightward* vehicles. Vehicles using the left lane are *leftward* vehicles.

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1 Vehicles in either lane may be a *transient vehicle* or *cruising vehicle*, but cruising is explicitly
2 disallowed by the basic rule yet effectively unavoidable once a certain volume threshold (level of
3 saturation) is obtained. Any leftward vehicle can be a blocking vehicle. The status of *blocking* is
4 conferred according to the *time tolerance* of the following vehicle, considering that the *time to pass* is
5 based on the *relative speeds* and vehicle lengths.

6 Leftward vehicles expediting a passing activity of one or more vehicles are considered *passing*
7 *vehicles*. Vehicles that are passing but fail to do so expeditiously are considered *micropassing* vehicles.
8 Vehicles remaining in the left lane indefinitely after completing a passing activity, whether approaching a
9 subsequent slower rightward vehicle or not, are *cruising* vehicles, irrespective of relative speed. Often,
10 *cruising* vehicles become *blocking* vehicles when a faster *following vehicle* approaches, whether that
11 faster vehicle is approaching *rightward* or *leftward*. Any *leading* vehicle that fails to vacate the left lane
12 for a *following vehicle* with an incipient higher speed is considered a *blocking* vehicle, whether *cruising*
13 or *micropassing*.

14 Even though a failure to vacate the left lane when cruising and maintaining a following distance
15 of a rightward vehicle may not inhibit traffic, such cruising does force all faster following vehicles to
16 make two lane change maneuvers in order to maintain speed. Mitigation of cruising and micropassing
17 therefore reduces crash risk for numerous vehicles, particularly those traveling at higher speeds. Even
18 when not inhibiting traffic, slower vehicles remaining in the right lane reduces conflicts for all faster
19 vehicles, maintaining order on the motorway. Signing indicating this is used beyond most interchange
20 ramps in several states, including Wisconsin, as displayed in the photograph below.



21
22 Figure 1 SLOWER TRAFFIC KEEP RIGHT signing along the Interstate 43
23 motorway in Wisconsin, USA
24

25 Various regulatory signing has been developed to discourage the presence of blocking and
26 cruising vehicles. Among the states in the United States, signs largely reflect statutes laying out two
27 distinct approaches. One approach is to preserve the left-most lane for passing only, irrespective of

1 relative speeds. The other approach is to direct slower traffic to remain right or move right. Neither
 2 approach explicitly directs traffic to expedite passing, although statutes requiring traffic to KEEP RIGHT
 3 EXCEPT TO PASS can be cited in administrative and civil infractions involving *cruising* and
 4 *micropassing* alike.

5 **Defining the Blocking Vehicle**

6 The definition of a *blocking* vehicle is considered exclusively in terms of disruption to the existing speed,
 7 desired speed, or desired minimum headway of any following vehicle. Differences among vehicle
 8 operator perceptions prevent a fixed definition of a *blocking* vehicle. Vehicles with lower rates of power
 9 delivery and higher power-to-weight ratios may be less tolerant of *blocking* vehicles, particularly when
 10 approaching uphill grades. The balance between speed, deceleration, and power settings is expressed in
 11 the selection of headway by *following* vehicles.

12 In Figure 2, below, a rightward following vehicle “f” is approaching two vehicles. A *blocking*
 13 vehicle “b” is failing to expeditiously pass the rightward cruising vehicle “r”, or *micropassing*. Once the
 14 following vehicle reaches its minimum tolerance for following distance, expressed in terms of time, the
 15 vehicle operator will move into the left lane, where it becomes both a *following* and a *passing* vehicle.
 16 Where basic rule compliance exists, the speed of the vehicle will remain unchanged, or the operator may
 17 select a higher speed to expedite the passing maneuver. In this case, however, should the blocking
 18 vehicle fail to increase speed, the result is a reduction of the speed of the faster vehicle to control
 19 headway.



20
 21 Figure 2. Graphical description of an incipient passing maneuver wherein
 22 the fastest *passing* vehicle “f” is subjected to potential delay by a
 23 *micropassing* vehicle “b”, thereby a *blocking vehicle*

24 In many localities in the United States, passing on the right is legal (under specific
 25 circumstances), in contrast to the German Autobahn. Aggressive law enforcement might assume that
 26 behavior to be a violation of certain statutes in some regions. Even if passing on the right is possible
 27 without approaching any minimum tolerable headways, the *blocking vehicle* in the left lane is defined by
 28 its relative position and relative relationship to the rightward vehicle; rightward passing is assumed to be
 29 nonviable.

30

1 Crucial Relationship to Following Distance

2 Because *blocking* vehicles often incur following distances that are shorter than desirable at higher speeds,
3 particularly in conditions where demand exceeds that supported by Level of Service A or B^b, such
4 vehicles directly impact operations and increase crash risk. This observation is uniform on all motorways
5 worldwide, irrespective of the presence of speed restrictions and often despite the presence of traffic law
6 enforcement activity. The relationship between headway and speed is an expression of efficiency, being
7 determinants of the volume of a lane at any given screen line.

8 Headways are a function of speed and following distance. Reducing the occurrence of sub-
9 optimal headways reduces the likelihood of speed and/or lane changes that disrupt the flow of vehicles in
10 a lane or group of lanes. In this sense, the presence of an auxiliary lane allows for headway management
11 by *following* vehicles and those intending to pass, so long as passing is expedited to ensure the
12 availability of the auxiliary lane for other vehicles. Expeditious passing reduces the workload of the
13 vehicle operators using the passing lane and reduces the likelihood of speed variability leading to sub-
14 optimal headways.

15 Maintaining Left Lane Availability

16 The relationship between workload and Level of Service in the context of auxiliary lane availability is
17 likely the most important finding of this paper. The availability of the passing lane on motorways is
18 directly correlated theoretical behavioral safety performance, is likely associated with improvements in
19 actual safety performance, and likely incurs dramatic public health and societal benefits across a wide
20 variety of measurement metrics associated with human interaction and social cohesion.

^b The computational and observational methods for determining or evaluating the Level of Service (LOS) are described in the *Highway Capacity Manual*, published by the Transportation Research Board of the National Academies. In recent years, some activists have attempted to diminish the use of LOS as a performance metric in urban environments at signalized intersections. The applicability of LOS to motorway segments is invaluable, however, because it provides a distinct correlation between volume, capacity, and, most importantly, the inhibition of lane changes by vehicles. Inhibition of lane changes reduces the overall value obtained by operators of vehicles with more flexible performance profiles. Inhibition of lane changes also incurs disbenefits in terms of safety because following distances are reduced in nearly all flow and maneuvering regimes.

1 **MODEL DEVELOPMENT**

2 For this research, the development of a model to address passing behavior considers both the functional
3 activity and the measured relationships based on vehicle states.

4 Functionally, passing maneuvers on same-direction roadways involve observation, perception,
5 reaction, and management of the vehicle controls on the part of the vehicle operator. Vehicle operators
6 must assess following distance, gap length, relative speed, and the rate of change in the gap length. Lane
7 change maneuvers are well-represented in the literature, typically understood in the United States to
8 involve vehicles traveling within the pace, where large differences in vehicle speeds are not expected.
9 Operation in an adjacent lane involves the assessment of leading traffic and precedes a second gap
10 selection exercise and a lane change maneuver to the right.

11 Vehicle operator perception of delay is inferred from various changes in traffic flow experienced
12 by the operator. A speed adjustment, headway adjustment, and time following a blocking vehicle are all
13 factors in the behavioral response to a blocking vehicle. The time required by a vehicle for passing is
14 therefore the dominant metric for assessing the road user experience. Variables used in passing equation
15 are provided in Table 1 below.

16 **Distance and Time Relationships**

17 The framework presented here assumes that conditions associated with motorways prevail. In localities
18 where unlimited speed conditions are in effect, the difference in speed between rightward vehicles ahead
19 and vehicles intending to pass can exceed 150 km/hr (93 mi/hr). The tolerance for following distances at
20 which lane changes are initiated are subsequently greater, although these tolerances vary based on terrain
21 and the capabilities of the passing vehicle in conjunction with operator proficiency, confidence,
22 perception of risk, and assessment of traffic conditions. In the United States, vehicle operators are more
23 likely to be inexperienced with vehicle speed differences exceeding 40 km/hr (25 mi/hr), given that the
24 pace on motorways in the United States occupies a smaller band.

25 Harmonizing observations irrespective of differences in vehicle speeds is accomplished with
26 respect to time rather than distance. Time is likewise another component of vehicle operator tolerance,
27 particularly with respect to blocking vehicles. With respect to time, blocking vehicles are therefore those
28 that occupy the left lane for more time than is expected by a following vehicle with an intended higher
29 speed. Time is also the means of measuring headways and following distances, which are functionally
30 equivalent for most scenarios.

31 **Operational Regimes**

32 The model developed for this research assesses the relative position and space-time relationship of
33 vehicles in the flow of traffic and characterizes vehicle activity according to time. Vehicle descriptions
34 from the introduction^c characterize the degree to which vehicles inhibit the flow of traffic.

^c Refer to pages 3 and 6 of this document for a review of the characterization of various vehicles with respect to position, activity, and duration of occupancy in the passing lane.

1 ***Typical State***

2 During typical operation that is compliant with recommended following distances, vehicles will exhibit a
3 headway of two (2) or even three (3) seconds, which is nearly equivalent to a following gap time of the
4 same duration. Competent or otherwise lawful drivers will allow additional time behind large vehicles,
5 during inclement weather, and in lighter traffic. In vehicles equipped with Automated Driving Assistance
6 System (ADAS) features, following distances can be set using Adaptive Cruise Control (ACC); some
7 ACC systems will reduce vehicle speed to maintain following distance, a means of managing headway
8 and reducing the risk of a rear-end collision.

9 ***Functional Description of Passing Activity***

10 A rightward vehicle becomes a passing vehicle as soon as the lane change maneuver leftward is initiated.
11 Prior to this, following rightward vehicles approaching another rightward vehicle are considered *incipient*
12 *passing vehicles*. The determination of this designation varies according to the difference in speed and
13 acceptable headways.

14 The passing maneuver itself is defined as a deviation from the rightward position. In some cases,
15 this deviation involves travel closer to the pavement markings or joint separating the rightward lane from
16 the leftward lane. In this analysis, that behavior is not included in the passing equation. However, the
17 time taken to close from the earliest acceptable lane change headway to the critical headway is included,
18 as the expectation of following vehicles is that a lane change could occur at any time after the acceptable
19 lane change headway is achieved.

20 ***Closure to Critical Following Distance***

21 Vehicle operators approaching another vehicle from behind must monitor the vehicle ahead and adjust
22 speed as needed to complete the task of closure to a critical headway. In practice, this is a following
23 distance that correlates to time. Following distances of 2 to 3 seconds are desirable and provide for
24 adequate perception-reaction time in most circumstances.

25 Observations conducted for this research effort indicate variations between selected following
26 distances according to the circumstances, outlined in the following three scenarios:

- 27 1. A rightward following vehicle approaches a slower rightward vehicle and executes a
28 leftward lane change. Observed following distances range from 10 seconds to 1 seconds.
- 29 2. A rightward following vehicle approaches a slower rightward vehicle and cannot execute
30 a leftward lane change, thus following the leading vehicle until the left lane is clear.
31 Observed following distances range from 5 seconds to 1 second.
- 32 3. A leftward vehicle (either cruising or having just completed a lane change maneuver)
33 approaches a leading but slower leftward vehicle. During this research effort, observed
34 headways ranged from 3 seconds (uncommon) to less than one vehicle length, often less
35 than 0.5 seconds, or 15 meters (approximately 50 feet, or two car lengths) at typical free-
36 flow speeds. Occasionally, following distances of less than one car length were
37 observed.

1 Observed headways in the latter scenario are often inadequate to accommodate the perception-
2 reaction time (PRT) necessary in the event of an immediate braking activity of the leading vehicle,
3 increasing the risk of a high-speed rear-end collision. In recognition of this risk, following too closely is a
4 term used in police crash reports regarding the selection of an inappropriate following distance.

5 ***Incipient Passing and Leftward Lane Change***

6 As the following distance decreases and vehicle operators assess the position and relative speeds of other
7 vehicles, including vehicles ahead, vehicle operators typically prepare for a lane change maneuver.
8 During this stage, a passing maneuver is evaluated and executed as the following distance reaches the
9 acceptable tolerance. The presence of other vehicles can incur a lane change sooner than what is typical
10 (larger headway) or later than what is typical (shorter headway), particularly when accommodating a
11 leftward vehicle that will pass prior to the subject vehicle executing the lane change maneuver.

12 Observations conducted during the course of this research activity indicated that most vehicle
13 operators will adjust vehicle speed to avoid headways of less than one (1) second, while inattentive
14 vehicle operators with poor perception capabilities may execute a lane change with headways of up to 15
15 seconds, even if the rate of change in the headway does not present a hazard.

16 ***Envelope Approach, Maintenance, and Departure***

17 During this stage of the passing activity, which follows the closure to critical headway, incipient pass, and
18 leftward lane change stages, the following distance of the leftward vehicle with respect to the rear face of
19 the rightward vehicle is reduced to zero. The subject vehicle then moves alongside the rightward vehicle
20 and continues in the left lane until a headway of sufficient tolerance is obtained. Some vehicle operators
21 will accelerate slightly during the stage, particularly alongside larger and heavier vehicles. When vehicles
22 discharging airborne debris are in the right lane, a passing vehicle may maintain a longer following
23 distance

24 ***Rightward Lane Change***

25 The basic rule informs vehicle operators that continued operation in the left lane is not allowable unless a
26 passing activity is occurring. Operators therefore seek the earliest opportunity to conduct a rightward lane
27 change, which is typically predicated on reaching a minimum leading distance, which courteously allows
28 for the rightward vehicle to maintain speed in conjunction with a desirable following distance.

29 Driver education programs suggest various ways to ensure that an adequate leading distance is
30 offered by the passing vehicle. One such method involves visually determining that both headlights of
31 the following vehicle are visible in the rear-view mirror of the passing vehicle. Operators of vehicles with
32 blind-spot monitoring technology may depend on the indications afforded by the system rather than by an
33 observational rule. In some cases, the duration over which these systems indicate a blind spot may not
34 provide sufficient following distance for the rightward vehicle following a rightward lane change by the
35 passing vehicle. Maintenance of leading distances by passing vehicles (equivalent to following distance
36 for the following rightward vehicles) impacts headway and the selected speeds of other vehicles.

1 Driver education and road safety program materials typically suggest that additional distance be
 2 afforded when passing trucks. The leading distance afforded prior to a lane change to the right thereby
 3 varies according to the speed of the passing vehicle, any acceleration of the passing vehicle, the relative
 4 change in speeds of the relevant vehicles, and the speed of the rightward vehicle.

5 ***Downstream Interactions***

6 While not considered part of the passing maneuver phase that blocks the path of other vehicles, a
 7 downstream vehicle can incur speed changes by the passed vehicle if the rightward lane change occurs too
 8 soon and the selected leading distance incurs a speed change or lane change by a rightward vehicle.

9 **Motorway Passing Equation**

10 Developed in support of research activities, the motorway passing equation expresses the various stages
 11 of the passing maneuver as a sum of the time required to conduct each phase, as described above. Time is
 12 related to selected speeds, distances between vehicles, and vehicle lengths, with speed and distances
 13 between vehicles being variable.

t	time (seconds)	time required for completion of various stages, variable with speed
s	speed (km/hr)	speed of vehicles, independent
d	distance (meters)	distance between vehicle faces, e.g., headway, variable with speed
l	length (meters)	length of vehicles, independent

15 Table 1 List of variables used in the motorway passing equation
 16

17 For the purposes of the equation, all passing maneuvers are considered fulfilled and the passing
 18 vehicle is uniformly referred to with a subscript *p*, irrespective of position. Positions include rightward
 19 following, leftward following, leftward adjacent (within the lateral projection of the slower vehicle's
 20 longitudinal envelope), leftward leading, or rightward leading vehicle. The relative time achieved
 21 determines the passing vehicle's status, whether expediting or micropassing. A cruising vehicle is not
 22 initially positioned rightward and likewise will not be positioned rightward at the conclusion of the pass.

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1 In addition to considering the time required to conduct each phase of the passing maneuver, the
 2 Motorway Passing Equations also consider the speeds (s) of the passing and rightward vehicles, the
 3 distances between the following vehicle and the slower vehicle (upstream), and the distances between the
 4 slower vehicle and the leading vehicle (downstream). Vehicle lengths are also referenced as l_p and l_r , for
 5 the passing and rightward vehicles, respectively.

6

u	upstream (d, l)	denotes a vehicle upstream (following) of another vehicle
e	envelope (position)	denotes a vehicle that is occupying any portion of the lateral envelope of an adjacent vehicle
p	passing (position, t)	denotes a vehicle position in a lane to the left of rightward vehicles; denotes the time for the entirety of the passing activity, from the minimum following headway to the minimum leading headway, which may not include lane change activities
d	downstream (d, t)	vehicles ahead of rightward and followed passing vehicles are considered downstream, or further along the roadway
r	rightward (position)	denotes a vehicle position in a lane to the right of the passing vehicle
l	leftward (position)	denotes a vehicle position in the lane to the left of the vehicle being passed.

7
8
9

Table 2 List of subscripts designating position and other references for time (t), distance (d), and vehicle length (l) variables

10 Various subscripts pertaining to position and stages of the passing activity are applied to distinct
 11 time intervals, t . These terms of the passing equation, derived from speed, distance, and length variables
 12 and assigned by position and stage, are listed in Table 3 on the following page.

13

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Term	Definition	Function Notes	Typical Values
t	total time occupying left lane, typically greater than t_p	$t = t_{fu} + t_l + t_u + t_e + t_d + t_r$	Less than 30 seconds is desirable for interactions between passenger cars
t_{fu}	time from earliest lane change opportunity to minimum following distance	Variable, depends on presence and relative speeds of leftward vehicles (both following and leading) attention, and tolerance of vehicle operators	Typically 5 to 30 seconds
t_l	time moving leftward	Primarily a function of vehicle speed and lateral acceleration tolerance, but influenced by presence of other vehicles	Typically 3 to 5 seconds
t_u	time occupying left lane, upstream and clear of rightward vehicle	Function of relative speeds, s_p and s_r , and initial d_u	Typically two or three times t_e
t_e	time adjacent to the rightward vehicle's envelope	Function of relative speeds s_p and s_r and length of rightward vehicle, l_r ; a subset of t	Typically 2 to 10 seconds for cars and 8 to 30 seconds when passing trucks
t_p	total time passing rightward vehicle	Function of relative speeds (s_p and s_r), length of rightward vehicle (l_r), and following distance tolerances	Sum of t_u , t_e , and t_p , desirable if less than 45 seconds
t_d	time occupying left lane, downstream and clear of rightward vehicle	Function of relative speeds (s_p and s_r) and final d_d , related to following distance tolerances, often reduced when followed too closely	Typically 8 seconds, more when truck capabilities are respected
t_r	time moving rightward	Primarily function of vehicle speed and lateral acceleration tolerance	Typically 3 to 5 seconds
t_{fd}	time spent achieving the desired following distance ahead of the (leading) passed vehicle	Function of relative speeds and leading distance tolerance	Ranges from 0 seconds to long durations, particularly if initial speed difference is small

1 Table 3 Time variables used in the motorway passing equation

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1 **Passing Activity Characterization**

2 A non-compliant passing activity occurs whenever a leftward vehicle fails to vacate the left lane for faster
 3 traffic or upon achieving an acceptable headway in front of the leading rightward vehicle. The Motorway
 4 Passing Equation can be used to determine the various positions based on the vehicle speeds and lengths.

5 In general, the characteristics of non-compliant and blocking vehicles can be expressed in terms
 6 of a variance from the ideal or typical numbers in the motorway passing equation.

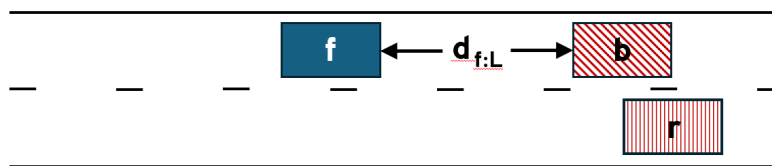
7 **Micropassing Vehicle**

8 A *micropassing vehicle* was defined earlier as a vehicle that fails to expedite a passing maneuver. In
 9 practice, this means that the time for the overall passing maneuver is protracted beyond what would be
 10 expected and beyond the tolerance of the operator of a following vehicle. This is typically the case when
 11 the value for t_p exceeds 30 seconds for car interactions and 45 seconds when a car is passing a truck. The
 12 duration of the time spent passing (time spent fully in the left lane) is directly related to the difference in
 13 the vehicle speeds.

14 The depictions in the figure below indicate the position of a *blocking* vehicle, *b*, just prior to
 15 entering the envelope of the rightward vehicle. The disrupted passing activity is caused by the
 16 *micropassing* vehicle, which is a *blocking* vehicle due to the failure of the operator to vacate the left lane
 17 and the subsequent change in speed of following leftward vehicles.



18 **DEPICTION 1**
 19 VEHICLE POSITIONS AT TIME $t = 0$ sec, $d = 1450$ ft
 20



21 **DEPICTION 2**
 22 VEHICLE POSITIONS AT TIME $t = 10$, $d = 200$ ft
 23

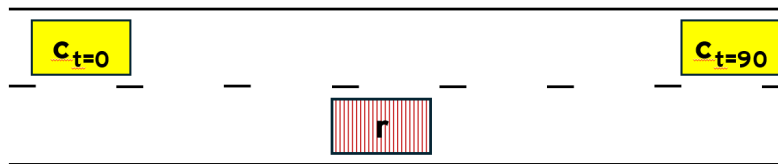
24 Figure 3 Vehicle Position Diagrams, Micropassing Activity

25

1 In practice, the operators of micropassing vehicles can mitigate traffic hazards by increasing
 2 speed by even as little as 3 km/hr (~2 mi/hr). Referencing Figure 4, if vehicle *b* had increased its speed
 3 by 2 mi/hr prior to entering the envelope, its passing time would have been reduced dramatically and its
 4 speed relative to the rightward vehicle would have tripled, from 1 ft/sec to 3 ft/sec.

5 **Cruising Vehicle**

6 A *cruising vehicle* is characterized in this research as a vehicle that enters the left lane well ahead of the
 7 critical following distance and/or fails to vacate the left lane upon reaching the critical leading distance.
 8 For some cruising vehicles, t_u and t_d appear to be infinite from the perspective of vehicle *r*. Any cruising
 9 vehicle can be considered a *micropassing vehicle* when t_e exceeds the tolerable value, irrespective of the
 10 values for t_u and t_d .



12
 13 Figure 4 Vehicle Position Diagram, Cruising Activity

14 In the scenario presented in Figure 4, above, the cruising vehicle has far exceeded 30 seconds in
 15 the left lane. If no downstream rightward vehicles are present, the corollary of the basic rule, KEEP
 16 RIGHT EXCEPT TO PASS, demands that the cruising vehicle vacate the left lane.

17 Research activities generally indicated that the decision to vacate the left lane is largely a function
 18 of the anticipated time spent in the right lane prior to reaching the critical following distance upon
 19 approach to a subsequent downstream rightward vehicle. A minimum time in the right lane of 10 seconds
 20 is considered tolerable, while 15 to 30 seconds is considered comfortable.

21 **Cruising Vehicles in Unlimited Zones**

22 In Germany, cruising vehicles appear to be more commonplace because the higher speeds of
 23 passing vehicles (160 to 250 km/hr) reduce the time required to cover longer headways between
 24 subsequent rightward vehicles. Despite this, however, cruising vehicles are rarely blocking vehicles.
 25 Federal statutes in Germany govern the behavior of passing vehicles, and nearly all encountered cruising
 26 vehicles observed in the field by the authors vacated the left lane without prompting upon recognition of
 27 an approaching leftward vehicle.

28 In many cases, the speed differential between the leftward following (but non-blocked) vehicle
 29 and the cruising vehicle exceeded 50 km/hr (30 mi/hr), although willingness to vacate the left lane was
 30 similar even at lesser speed differentials. Of particular note is that the assumed relative capabilities and
 31 intentions of interacting vehicles appeared to influence the decision to vacate the left lane or increase

1 speed to complete a subsequent passing maneuver. In Germany, operators of cruising vehicles exhibited
 2 increased willingness to move right when premium-segment vehicles were observed approaching from
 3 behind. This was less pronounced in Poland; the opposite appears to be true^d in the United States.

4 **Review of State Statutes**

5 In the United States of America, signing for the use of the left lane on motorways and multi-lane high-
 6 speed roads takes various forms, generally being consistent within a given state. A 2018 review¹ of state
 7 statutes found that 29 states require that vehicles “traveling slower than the surrounding traffic must be in
 8 the right lane.” The same review found that 11 states reserve the left lane only for passing and for
 9 preparing to exit the roadway from the left side, such as at a left exit or through the use of a median
 10 opening. A summary of the generalized statutes compiled in in 2022 is included below in Table 4.

Generalized Statute	Jurisdictions
<p style="text-align: center;">SLOWER TRAFFIC KEEP RIGHT</p>	<p>AL, AZ, AR, CA, CO, CT, GA, HI, ID, IN, IA, KS, KY, LA, ME (posted less than 65 m/hr), MN, MS, NE, NH, NM, NY, ND, OK, OR, PA, RI, SC, SD, TN, TX, UT, VT, VA, WV, WI, WY</p>
<p style="text-align: center;">KEEP RIGHT EXCEPT TO PASS</p>	<p>AK, FL, IL, ME (posted 65 mi/hr and above), MD, MA, MI, MO, MT, NV, NJ, NC, OH, WA</p>
<p style="text-align: center;">DO NOT PASS ON RIGHT</p>	<p>NJ, [German Republic]</p>

12 Table 4 Summary of Generalized Statutes for Left Lane Use by Jurisdiction²

13
 14 Of note is the issue of relative speeds related to the SLOWER TRAFFIC KEEP RIGHT laws.
 15 For example, a vehicle in the left lane that is not passing must move right for a vehicle approaching, but it
 16 can return to the left lane upon being passed, as long as it does not impede the flow of traffic, given that
 17 there is no slower traffic with which it can be compared. This action defies the basic rule.

18 **Summary of Operational Impacts**

19 While operational impacts are imposed by the discrete obstruction to the flow of traffic, the impacts are
 20 conveyed and exacerbated by human factors, including those stemming from cognitive limitations and
 21 behavioral outcomes. Behavioral outcomes stem from user expectations and a desire for compliance with
 22 the requirements of both statutes and social order.

^d A search for the term “BMW” on nearly any social media channel will produce results that might convince a person that BMW drivers in the United States are the worst in the world. Prejudiced attitudes toward other road users indicates a need to further assess various social-behavioral disorders that shape lane use courtesy attitudes.

1 A post on the popular social conversation forum Reddit asked the following question: “[I]s
2 everyone that drives here a dumbass? How do you not see the line of traffic you’re creating by hogging
3 the lane while going 60 mph while texting[?]”³ The evident impact is the long moving queue of vehicles
4 behind a vehicle whose operator is failing to complete a passing maneuver, hence, operating a *blocking*
5 *vehicle*. Observations during the course of this research indicate that where volumes approach 1500
6 vehicles per hour in two lanes, these queues can approach six to eight cars in length in less than 90
7 seconds, causing transient reductions in Level of Service and impacts to crash risk, particularly if heavy
8 vehicles and/or longer vehicles are involved.

9 Decreased following distances, reduced on-task attention, and physiological effects such as
10 increased heart rate and adrenaline response can create an increased risk of collisions, particularly rear-
11 end collisions during inclement weather and low visibility. For vehicles that persist in the left lane upon
12 completion of a pass, known as *cruising*, additional risks are conferred to the occupants of other vehicles,
13 due to the need to change lanes to the right in order to maintain the desired speed.

14 **Impacts of Vehicle Automation**

15 Vehicles with speed governors and users who rely on cruise control when passing present a particular
16 challenge with respect motorway operations. An overtaking vehicle that fails to exceed the speed of the
17 vehicle(s) in the adjacent lanes is not vacating the left lane. This phenomenon, an unintentional
18 micropassing activity, will become more prevalent with the fleet penetration of automated vehicles
19 relying on software programmed to never exceed the posted speed limit. Mitigating the hazard of failed
20 passing maneuvers will require an acceptance of speeds in excess of the posted speed limit.

21 Vehicles with ADAS equipment allow for the adjustment of tolerances for the ACC, which
22 influences the time that vehicles occupy the left lane during a passing maneuver. While some vehicles
23 govern speeds so as to prohibit exceeding the speed limit, other vehicles with Level 2 capabilities
24 (reference the Society of Automotive Engineers Levels of Driving Automation) allow for setting an
25 “offset” from the speed limit, either as a percentage or a discrete value. This offset is applied to the cruise
26 speed, however, and a small difference between the speed of rightward vehicle and the incipient passing
27 vehicle can cause ADAS-equipped vehicles to become blocking vehicles during passing maneuvers when
28 self-driving capabilities are engaged. Intervention by the supervising operator would be necessary to
29 avoid blocking vehicle status in those cases.

30

31

METHODOLOGY AND LIMITATIONS

Four activities supported the development of results for this research. Activities included ongoing field observations, an inventory of typical traffic signing, passing model development and testing, and an assessment of interventional techniques and the localized effects of traffic signing on behavior.

Field observations of left lane operations were made along roadway segments and in spot locations spanning a timeframe of ten years from 2014 to 2024. Based on these observations, a time-space model for motorway passing maneuvers was developed in 2022. Model validation was then conducted along roadway segments between 2022 and 2024. Field observations in both periods included an inventory of signing and observations related to the effectiveness of the signing, both systemically and tactically.

Because this research was conducted with limited resources and support, observations were largely heuristic and identified general trends. Recorded datasets are not available. This research is based on the repeatability of results when similar traffic conditions and research vehicle operations techniques are employed, demonstrating the consistency of human behavior across regions. These activities supported the development of practice recommendations and recommendations for ongoing research activities.

Excluded Conditions

Compliance with the basic rule requires that the left lane be available for use by vehicles irrespective of vehicle occupancy and in conditions where use of the left lane is not necessary for non-passing maneuvers. For this research, a list of excluded conditions was developed and is presented in the list below.

1. Motorway segments with high-occupancy vehicle lanes, express toll lanes, or other lanes where access to the left-most lane is restricted by vehicle occupancy and/or the requirement for payment
2. Rural divided high-speed highways and urban multi-lane arterials where left turns are accommodated, either from the mainline or from the intersecting roadways; longer distances between intersections can exacerbate the assumption of motorway speeds
3. Motorway segments featuring deceleration lanes or tapers of insufficient distance to permit deceleration to the minimum statutory or posted speed
4. Motorway segments with an inconsistent number of basic lanes^e along distances of less than three (3) miles

^e In this use, “basic lanes” does not correlate to the “basic rule”, but rather refers to a motorway design concept that involves ensuring that the same number of continuing lanes is carried through interchanges along segments with similar traffic volumes. In practice, where right lanes are terminated as mandatory exiting lanes, the concept of basic lanes falls short of the intended outcomes, which is to avoid disruption in traffic flow. In fact, if the number of basic lanes is counted from the left, then the effects of lane terminations and lane changes by heavier and slower vehicles are exacerbated. The most basic lane ought to be the right-most lane, where travel is expected.

1 Not excluded were motorways where vehicles classified as trucks (by wheel count, length,
2 weight, or other characteristics) are not prohibited from using the left-most of three or more lanes. In
3 Wisconsin, one of the regions where observations were conducted, trucks are not prohibited from using
4 the left lane of roadways with more than two (2) lanes in the direction of travel. Examination of the
5 impacts of heavy vehicle operations in these unique circumstances provides a contrast against states with
6 specific and consistent restrictions, including South Carolina.

7 While field observations were conducted along segments with conditions matching those in the
8 list below, the generalized results of observations in the excluded segments are not used to determine
9 basic rule compliance in a region or along motorway segments with particular characteristics.

10 **Research Techniques**

11 Researchers conducted passive observations and observations in concert with active intervention
12 techniques. Passive observation of a blocking vehicle involved maintaining speed behind a vehicle in the
13 right lane so as to avoid compelling a change in speed; a three-second following distance was typically
14 selected. Both researchers employed passive observation techniques in mixed traffic and from fixed
15 vantage points.

16 In some localities, research activities were conducted using various vehicle types and both
17 passive and active techniques. Observations in all localities were conducted on both motorways and
18 multi-lane divided high-speed rural roads with limited intersections. In Wisconsin, Washington State,
19 and South Dakota, most of the latter facilities did not include traffic signals. In Ohio and Maryland,
20 isolated rural traffic signals were commonplace on these non-motorway facilities.

21 Across an estimated 3,000 hours of observation *in situ*, researchers interacted with and/or
22 observed approximately 100,000 discrete blocking vehicles, with durations of observation exceeding 90
23 seconds in a fraction of the observations. Due to the limitations of the observational environment and in
24 order to promote attention to the driving task, particularly in solo occupancy situations, researchers
25 compiled notes by memory and characterized the interactions in broad categories for later recall and
26 classification.

27 ***Passive Observation Techniques***

28 The majority of the research involved passive observations, where the posture of the vehicle and
29 illumination status were neutral, so as to not induce a reaction from other vehicles. Additionally,
30 researchers maintained following distances, even in mixed traffic and within moving queues of following
31 vehicles. This occasionally allowed for a vehicle to take a forward gap, whereupon the researchers would
32 increase the following distance again.

33 ***Active Intervention Techniques***

34 Active intervention techniques involved adjustments to the research vehicle's posture and illumination
35 status, conducted according to a controlled rubric. The corresponding author was the researcher solely
36 responsible for engaging in active intervention techniques for observation in mixed traffic. Active

1 intervention techniques were conducted along segments where regulatory signing was installed and along
2 segments where at least five minutes of driving had passed since the posting of a regulatory sign.

3 Active intervention trials with observations were conducted on various rural free-flow multi-lane
4 roads, with two longer contrast periods selected. One trial included long segments of Interstate 90,
5 Interstate 94, and U.S. Highway 12 in Washington State, Idaho, Montana, Wyoming, South Dakota, and
6 Minnesota, with observations conducted in 2021, 2023, and 2024, following on five years of passive
7 observations and pre-trial posture evaluations within the same regions. The other trial included Interstate
8 80 between Hammond, Indiana, and the Cleveland area, along with other selected roads in Pennsylvania,
9 Ontario, and Michigan, with observations conducted in July 2024.

10 In addition to the North American observations, an extensive (1500 kms) transit of motorways in
11 Germany and Poland involved active intervention techniques. On European motorways, intermittent
12 activation of the high beams is commonplace for an approaching vehicle to request that a leading vehicle
13 to vacate the left lane, often occurring well ahead of the critical following distance. This was observed
14 even irrespective of the potential for blocking behavior, and courtesy indication if overtaking intent.

15 ***Vehicle Posture***

16 Vehicle posture comprises the vehicle's position, following distance, and indications. Various vehicle
17 posture regimes were observed in pre-trial field observations. While sub-vehicle-length following
18 distances are common among *following vehicles*, even at speeds exceeding 120 km/hr (75 mi/hr), a two-
19 second following distance (2 sec) was achieved by researchers to avoid the risk associated with reduced
20 following distances and to demonstrate courtesy.

21 Occasional variances in the lateral position of the research vehicle served two purposes. The first
22 purpose was to provide for forward visibility, particularly around larger vehicles. The second purpose
23 was to increase the visibility of the research vehicle's headlights in the outside mirrors of the blocking
24 vehicle.

25 The most common indication of posture was sequenced use of the high beams. High beams can
26 be activated well ahead of approaching a blocking vehicle, at distances exceeding 500 meters
27 (approximately 1500 feet). Sequenced activation of the high beams is most commonly a three-burst
28 notice with a duration of approximately two seconds. In Germany, Poland, and some parts of the United
29 States, this was sufficient to obtain a response from the blocking or cruising vehicle. In other parts of the
30 United States, operators of blocking vehicles gave heed only when continuous sequenced bursts were
31 employed, and some did not give heed at all under any circumstances. A frequency of 40 activations per
32 minute was chosen to allow for differentiation between the sequenced bursts (which were more similar to
33 the three-burst method) and other types of sequenced headlight activations associated with emergency
34 response vehicles.

35



1
2 Figure 5 In unlimited zones (notice Intelligent Speed Assistance sign
3 recognition display in upper-left corner), speeds in excess of 200
4 km/hr are readily and continuously obtained on the German
5 Autobahn, even when passing cars and trucks.^f
6
7

8 Assessment of the posture of *blocking*, *following*, *tailing following*, and *rightward* vehicles
9 revealed opportunities for improved education and enforcement, particularly with regard to blocking
10 vehicles. Blocking vehicles often maintained a position relative to rightward vehicles such that the
11 blocking vehicle was in the blind spot of the rightward vehicle, particularly common when trucks were in
12 the right lane. Following vehicles, in addition to following closely, also drifted rightward on occasion,
13 even when rightward vehicles were present within the reaction envelope.

^f It is unlikely that autonomous vehicle manufacturers will accept this level of risk, a potential pathway for justifying electronically-enforced lane restrictions for autonomous vehicles that do not achieve parity with humans.^{SK}

SUMMARY OF OBSERVATIONS AND SIGNING INVENTORY

While it is possible to capture anecdotal evidence in conversation with individuals who frequently operate vehicles on motorways, a rigorous approach involving numerical measurements provided information on the operations most likely to inhibit the availability of the left lane. Researchers observed the presence of cruising vehicles, the following distances at which lane changes occurred, the durations of passing maneuvers, the lead distances at which vehicles vacated the left lane, the prevalence of turn indicator operation^g, the durations of lane changes, and speed variability during maneuvers for leftward passing vehicles (whether expediting or micropassing), leftward cruising vehicles, rightward vehicles, leading vehicles, and tailing vehicles.

Signing Inventory

A global signing inventory was conducted during field observations. In general, most signs conveyed information regarding traffic regulations and prohibitions. In the United States, regulatory signs with text were commonplace.

Sign Message	Placement	Localities
KEEP RIGHT EXCEPT TO PASS	Typically right side, occasionally left side	Michigan, Illinois (USA)
LEFT LANE FOR PASSING ONLY	Typically left side	Infrequently observed
SLOWER TRAFFIC KEEP RIGHT	Typically left side Occasionally right side	Wisconsin (USA) Indiana, Pennsylvania (USA)
SLOWER TRAFFIC MOVE RIGHT	Typically left side	Minnesota, USA

Table 5 Summary of traffic signing addressing left lane restrictions

^g Across the various states, vehicle code statutes are harmonized such that a motorist shall use a turn signal when changing lanes. However, motorist behavior is not consistent, even within regions of the same state. Compliance with this law in Maryland and Michigan is observed to be poor. Such an opinion might be subjective but when a neighboring state’s DOT calls it out on social media, the opinion carries some weight: <https://x.com/VaDOTNOVA/status/1818435680957042883>^{AG}

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1
2 Table 5 addresses static signing only, typically classified as “regulatory” signing in the United
3 States. Some motorway segments, particularly those on the Autobahn and in Northern Virginia
4 (Washington, DC, metropolitan area), Seattle, and Las Vegas operate with dynamic controls through an
5 active traffic management system. Most commonly, these signs display specific restrictions or
6 exemptions related to lane use control. For example, on the Autobahn in Germany, messages exclude
7 trucks from the left lanes during “stau” (German language, semi-colloquial, meaning periods of
8 congestion). In Seattle, Washington State, high-occupancy vehicle restrictions are temporarily lifted
9 during road work and the left lane becomes available for passing.



11
12 Figure 6 Changeable message sign on the Autobahn in Germany, entering a
13 restricted speed zone; the standard symbol sign conveys the meaning
14 that trucks are prohibited from occupying the left lane.
15

16 In European countries, symbolic signs indicating restrictions on passing are commonplace along
17 motorway segments, particularly in sections with more than two lanes in each direction, within
18 interchange areas, along uphill grades, and in areas where inclement weather and reduced visibility are
19 expected. While the majority of those restrictions are imposed with static signs, regularly-spaced
20 changeable message signs (mounted to the side) and overhead changeable message signs are also used to
21 prohibit trucks from the left lane in congested areas and during periods where traffic volumes are high. In
22 this way, the free-flow characteristics of the motorway are maintained by reducing the disruption of the
23 flow of traffic, just as is done with ramp meters.

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1 **Field Observations of Passing Behavior**

2 Field observations were conducted in five countries, listed below in Table 6. The prevalence of cruising
 3 and blocking behaviors is characterized for each locality. In general, these observations were conducted
 4 in free-flow conditions (Level of Service A or B⁴), in rural segments with two or three lanes in each
 5 direction, and during daylight conditions where the road surface was clear and dry. Atmospheric
 6 conditions varied, although observations were suspended in heavy rain and snow where visibility was
 7 reduced. The responsiveness of blocking vehicles to intervention techniques, described in the next
 8 section, is also broadly characterized in Table 5.

9

Locality	Period(s)	Blocking Behaviors	Responsiveness
Germany	2017, 2019, 2024	Rare to Occasional	Immediate
Poland	2024	Occasional	More likely
United Arab Emirates	2017, 2019	Common, particularly cruising	Inconsistent
South Dakota, USA	2014, 2020, 2023	Cruising occasional; trucks pass on long grades	Occasional
Texas, USA	2019, 2022	Widespread	Unlikely
Croatia	2018, 2019	Occasional	Immediate
California, USA	2017, 2021	Cruising ubiquitous	Unlikely
Wisconsin, USA	All Years	Cruising commonplace	Limited
Washington State, USA	All Years	Cruising commonplace; HOV network effects	Less likely
Maryland, USA	All Years	Cruising commonplace	Limited
Montana, USA	All Years	More likely for vehicles with trailing units	Limited
Ohio, USA (Turnpike)	2024	Micropassing commonplace	More likely
Ontario, Canada	2017, 2024	Cruising observed	Inconsistent
British Columbia, Canada	2016-2024	Micropassing commonplace, cruising widespread	Limited

10 Table 6 Summary of Field Observation Activities and Inferences

11

1 Findings from the field observation and model development activities were largely heuristic in
2 nature. While large datasets are not available for analysis, the efforts of researchers to conduct
3 observations over a long period of time allowed for pattern recognition, posture characterization, and the
4 characterization of regimes that allowed for model development.

5 Information in Table 6 above is a summary of the generalized observations from all observational
6 periods and presents specific observations related to interventional activities associated with vehicle
7 posture.

8 **Non-Compliant Passing Factors and Mitigation**

9 Specific operational effects associated with vehicles, traffic control devices, roadway design, and
10 behavior were also identified in the research activities. Very often, one or more of these effects
11 contributed to a non-compliant passing behavior.

12 ***Impacts of Heavy Vehicles***

13 Heavy vehicles include trucks, buses, and other large vehicles with power-to-weight ratios fractionally
14 less than that of cars. These vehicles cannot sustain speeds on uphill grades and many commercially-
15 regulated heavy vehicles are subjected to speed limiters. In the United States and the European Union,
16 commercial and government regulation of heavy vehicle speeds limits speeds to 100 km/hr for buses and
17 even as low as 80 km/hr for many trucks, even on motorways. Because of these limitations, operation of
18 trucks in the left-most lane is often prohibited by statute and signing.

19 Despite these prohibitions and the clear limitations of trucks, trucks were frequently observed
20 inhibiting traffic. Micropassing and cruising by trucks was commonplace in many states. Even on the
21 Autobahn, where enforcement of basic rule compliance is more common, trucks frequently violated
22 restrictions imposed by signing ahead of and along uphill grades.

23 ***Impacts of Inattentiveness***

24 While popular culture indicates a willingness to ascribe blocking activities to the motive of malice, it is
25 more likely that inattentiveness accounts for some blocking and cruising activities observed. Operating a
26 vehicle on the motorway involves a demanding set of tasks. Proper training and reminders of the special
27 obligations associated with operating a vehicle on the motorway hold the potential to reduce
28 inattentiveness. Enforcement activity focused solely on blocking and cruising can also raise awareness of
29 the need for attentive driving and compliance with lane use courtesy statutes and signing.

30

1 **Effects of Vehicle Posture**

2 A neutral vehicle posture was unlikely to generate a response from a blocking vehicle. The majority of
3 cruising vehicles failed to vacate the left lane upon reaching a leading distance of three seconds.

4 Sequenced activations of high beam headlights (flashing, as described earlier) incurred varying
5 effects. The type of vehicle and intensity of the sequenced activations did appear to correlate with
6 responsiveness. In general, the use of sequenced high-beam activations engendered increased
7 responsiveness. The list below contrasts various circumstances where flashing occurs.

- 8 • flashing from taller vehicles was more effective than shorter vehicles
- 9 • cruising vehicles were more likely to respond than micropassing vehicles
- 10 • flashing activations whilst in the left lane were more effective on all types of
11 blocking vehicles than those from the right lane
- 12 • flashing in a continuous sequence at a rate of 40 alterations per minute for more than
13 15 seconds was more effective than what is typically observed, which is three to five
14 alternations, with potential multiple discontinuous sequences
- 15 • earlier onset of continuous-sequence flashing was more effective than later onset;
16 earlier onset of flashing typically necessitated an earlier vacation of the left lane

17 In general, responsiveness to flashing appeared to correlate more strongly with a culture of
18 courtesy, which indicates regional variations.

19 **Effects of Traffic Signing**

20 Traffic signing with the messages outlined in Table 5 was present in approximately two-thirds of the
21 motorway segments whereupon observations and interventions were conducted. In the United States,
22 there was little observed correlation between the location of the traffic signing and the compliance of road
23 users. Interventional techniques did not appear to increase the effectiveness of traffic signing.

24 **Effects of Regional Variations**

25 Cultural courtesy, topography, and road network topology all appear to have an impact on compliance
26 with lane use statutes. Further study of these regional variations would consider these factors along with
27 understanding the contribution of driver education, enforcement emphases, and the use of social media to
28 discuss enforcement activities. The observations summarized in Table 6 indicate regional variations and
29 variations between behavior in the United States, Poland, Canada, and Germany.

30 Within the United States, lane use compliance associated with the termination of micropassing
31 activity was most apparent in central Pennsylvania and South Dakota. Avoidance of cruising was most
32 apparent in central Pennsylvania. Blocking activities were most prevalent in Maryland and Indiana.
33 These regional variations do not appear to correlate with the generalized statutes outlined in Table 4 or
34 the associated messages on regulatory signing described in Table 5.

35

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1 This lack of correlation suggests that statutes and signing, while formative and according to the
2 rule of law, are less effective than enforcement and cultural norms. Further to this theory, researchers
3 observed variations in the presence of blocking activities in areas where observed lane use courtesy was
4 more prevalent. On primary highways with a greater percentage of through traffic and out-of-area
5 number plates (“license plates”), blocking activities did not correlate strongly with what was observed on
6 lower-volume roads serving regional and interregional traffic.



8
9 Figure 7 View of the eastbound Indiana Toll Road at the near South Bend,
10 Indiana, USA. The trucks visible in the left lane had inhibited passing
11 vehicles for nearly two miles, a period of nearly two minutes.^h

12
13 The presence of trucks causes considerable inhibition of the availability of the left lane for
14 passing, particularly along segments where only two lanes are available in the direction of travel.
15 Inhibition of the left lane was observed to be more pronounced in hilly terrain, in areas with long uphill
16 grades, along corridors where development favored commercial and logistics operations, and in states
17 where statute fails to prohibit heavy vehicles from the left lanes.

18

^h Note the lack of dotted lane line markings and dotted extension markings and the incorrect selection of a warning sign ahead of a lane reduction taper.

1 RECOMMENDATIONS

2 Research activities indicated that selection of speed when passing influences the time to pass and
3 perception of improper passing by observers operating other vehicles. Approaches that reduce the time
4 spent occupying the left lane will reduce the likelihood of conflicts arising between blocking vehicles and
5 other passing vehicles. These approaches include recommendations addressing the following topics:

- 6 1. Speed management and statutory revisions
- 7 2. Geometric design and pavement marking revisions
- 8 3. Availability of left-side high-occupancy vehicle lanes
- 9 4. Lane use compliance enforcement and education
- 10 5. Dynamic traffic signing with the LUCID System, introduced by this paper

11 Statutory Speed Limits, Speed, and Facilitating Passing Activities

12 The basic rule reflects the reality that vehicle operators will be constrained in various ways by human
13 limitations and the limitations of various types of vehicles by allowing for flexibility and order. Despite
14 this, statutes, policies, and enforcement activities in the United States and Canada fail to adequately
15 reflect human capabilities and limitations related to operation of vehicles on motorways. Speed limits are
16 uniformly set below appropriate or comfortable operating speeds.

17 Heuristic observations in the United States, Europe, and the Middle East indicate a free-flow
18 speed for prevailing traffic of approximately 125 to 130 km/hr (80 to 85 mi/hr). In rural areas where
19 roadway geometry and cross section are generous, the majority of vehicle operators in the general-
20 purpose lanes (those not restricted by occupancy or vehicle type) will select speeds approaching 140
21 km/hr (90 mi/hr), particularly in areas where enforcement is less prevalent. In Germany, in unlimited
22 sections, even vehicles with modest power-to-weight ratios often exceeded 160 km/hr (100 mi/hr) when
23 passing trucks, a recognition that expedited passing reduces exposure when adjacent to the vehicle
24 envelope!

25 Revisions to statutes can reflect the reality of motorway operations with two general changes that
26 constitute scenario-based enforcement enabled by technology advancements in real-time monitoring and
27 measurement of traffic flow characteristics. These revisions include

- 28 a) codifying penalties only for speeds above the 95th-percentile rather than speeds above the
29 posted speed limit and prioritizing enforcement of order rather than speed compliance; and
- 30 b) allowing for various scenarios where higher speeds do not constitute an infraction. The most
31 obvious scenario is the need to increase speed when passing.

32 Allowing vehicle operators to expedite a passing maneuver by marginally exceeding the speed
33 limit or the prevailing speed of traffic reduces the time a vehicle will spend in the left lane and alongside
34 slower vehicles. In South Dakota, Codified Law 32-25-28 allows a vehicle to exceed the posted speed
35 limit when passing on a two-lane highway. This statute is cited at the top of the next page.

36

32-25-28. Exceeding posted speed limit permitted under certain conditions.

The speed limit is increased by ten miles per hour over the posted speed limit, if a person is driving a vehicle that is:

- (1) On a two-lane highway that has one lane for each direction of travel;
- (2) On a highway with a posted speed limit that is equal to or exceeds sixty-five miles per hour;
- (3) Overtaking and passing another vehicle proceeding in the same direction of travel; and
- (4) Passing a vehicle that is moving slower than the posted speed limit.

If statutes were to reflect that higher speeds are permissible when passing using the left lane, regulatory signing can reinforce education and enforcement campaigns. Recommended regulatory signing in Figure 8, below, includes a sign clearly stating that an increase in speed is required to expedite a pass. Initially, field evaluations of sign effectiveness could be conducted ahead of long grades, at the beginning of tangent sections, and in areas where probe data indicates that congestion is recurring.

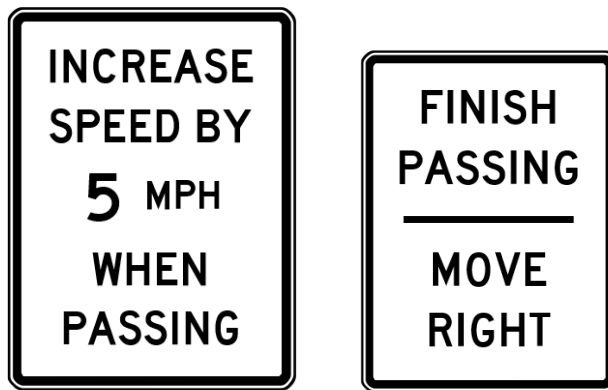


Figure 8 Proposed sign sequence indicating that increased speeds when passing are permitted and expedited passing is required

The second sign in the figure above is an adaptation of the SLOWER TRAFFIC MOVE RIGHT signs used by the Minnesota Department of Transportation. This sign could be placed at the beginning of long grades, along tangent sections in advance of horizontal curves, and at other locations where the availability of the left lane would be improved by the absence of inhibiting vehicles.

1 **Geometric Design and Pavement Markings**

2 Geometric design, lane arrangement, and pavement markings are all used to guide vehicles within the
3 traveled way by inhibiting or promoting movements based on the degree of desirability and hazard. On
4 motorways, lane arrangements should reduce the need for lane changes for continuing traffic, particularly
5 lane changes by heavy vehicles and vehicles that are generally moving more slowly than the prevailing
6 speed of traffic.

7 Roadway segments with higher volumes present the opportunity to add capacityⁱ in pursuit of the
8 goals of reducing queue spillback, improving operations on sections where slower speeds are observed,
9 and increasing the availability of the left lane. Left lane availability can be increased by mitigating
10 conditions that incur lane changes to the left (generally to avoid slower vehicles) and/or by providing use
11 of an additional lane on the left, even if that lane is provided for short distances.

12 ***Acceleration Lanes***

13 Acceleration lanes (also known as Speed Change Lanes) allow vehicle operators entering the motorway to
14 harmonize speed with adjacent traffic, select a gap, and execute a lane change maneuver. Acceleration
15 lanes on motorways are preferable to the AASHTO “tapered entry” in that these lanes allow operators to
16 execute several tasks simultaneously and discretely, rather than complicating the lane change task with a
17 speed change, curvature, and sub-optimal viewing angles from the operator’s seat. On motorways,
18 acceleration lanes that are longer than the minimum distance specified in various design resources can
19 introduce resilience, particularly in areas where growth in heavy vehicle traffic is expected.

20 Signing for longer acceleration lanes occasionally consists of a RIGHT LANE ENDS (W9-2)
21 warning sign. For acceleration lanes of any length, a proposed MERGE with Type A ARROW sign can
22 be used near the beginning of the lane reduction taper, clearly identifying the location where the
23 acceleration lane ends. Additionally, enhanced delineation can be installed along the taper for nighttime
24 conspicuity.



25
26 Figure 9 MERGE with *MUTCD* Type A ARROW warning sign, used by the
27 Minnesota Department of Transportation

ⁱ Despite the insistence to the contrary of anti-roadway and anti-car activists, adding capacity to the motorway system attracts traffic to the highest-order roadway links and reduces demand on lower-order links. Facilitating access to the highest-order links by reducing intersection and network delay serves the demand induced by development and corresponding economic activity and reduces the congestion caused by density.

1 Pavement markings in acceleration lanes aid vehicle operators in understanding the purpose of
2 the lane and recognizing where the acceleration lane terminates. A pattern consisting of a solid white line
3 adjacent to a dotted lane line can be used along the length of the full width of the lane to discourage lane
4 changes into the lane. When followed by a dotted extension line, the shorter lines and a narrower
5 marking width provide a clear differentiation between the available lane and the length of the taper.^j

6 ***Deceleration Lanes***

7 Deceleration lanes allow vehicle operators exiting the motorway to reduce speed in a separate lane,
8 mitigating conflicts with vehicles in the right-most lane. Because deceleration lanes aid continuing heavy
9 vehicles in maintaining speed and avoiding drastic or substantial speed reductions, they incur operational,
10 fuel economy, and emissions benefits. An activity analysis of entering a deceleration lane indicates that
11 the risk of task saturation is lower, although the reduction in task saturation risk is not as pronounced as
12 with parallel-style acceleration lane installations.

13 Signing for deceleration lanes typically consists of a guide sign and, if specified, various warning
14 signs and advisory speed signs included in Part 2 of the *MUTCD*. In Germany, deceleration lanes are
15 signed with “countdown” signs indicating 300, 200, and 100 meter distances to the departure taper or
16 beginning of the first horizontal curve. In Colorado, the R3-5 RIGHT TURN ONLY and other R3-series
17 signs have been adapted for use alongside the full width of a deceleration or exit only lane.

18 Pavement markings for deceleration lanes likewise aid vehicle operators in recognizing that such
19 lanes are non-continuing lanes. A pattern consisting of a dotted extension line along the opening taper, a
20 dotted lane line along the full width, and a solid lane line ahead of the departure taper provides
21 increasingly-restrictive markings that are differentiated by position along the lane and differentiated from
22 a continuing lane. Continuing traffic is discouraged from entering the lane by the dotted extension
23 markings, which would not be present if a continuing lane were added on the right. In California and
24 Washington State, lane use arrows are used, featuring the very long aspect ratio typical of freeway-type
25 markings, which are intended to be recognized at speed.

26 ***Transient Motorway Passing Lanes***

27 In Germany and in Missouri (USA), motorway operators have installed passing lanes on the left side of
28 the roadway along uphill grades. The provision of an additional lane on the left side of the roadway
29 creates immediate availability. Trucks and slower vehicles are not required to conduct a lane change to
30 the right, as would be the case where a climbing lane is provided. In general, the flow of traffic remains
31 stabilized while the left lane remains available for faster and more flexible vehicles.

32 Selection of pavement markings indicating the special use of the left lane should have the
33 intention of reducing the likelihood of errant lane changes. Specifically, marking of the left lane as
34 reserved solely for passing can be accomplished with a new marking pattern (perhaps 1:1 cycles
35 continuous) and the use of letters and symbols with accompanying signing.

^j In Massachusetts, updated State standard plans reflect this differentiation and adaptation to the needs of
autonomous vehicle camera systems and improved information for human vehicle operators

1 ***Restriction on Off-Peak Use of Left-Side HOV Lanes***

2 In Washington State, Virginia, Maryland, California, Minnesota, and other states, left-side HOV lanes are
3 commonplace in metropolitan areas. On some motorway segments, the restrictions are in place solely
4 during commuting hours (e.g., 6 a.m. to 9 a.m.), throughout the day (e.g., 5 a.m. to 7 p.m.), or,
5 occasionally and more commonplace with HOT facilities, restrictions are dynamically assigned.

6 When HOV lanes are not restricted to HOV traffic only, some vehicles still cruise in the HOV
7 lane, either by habit or for individual convenience. Other vehicles appear to avoid the HOV lane even
8 when it is not restricted to multi-occupant vehicles. These HOV lanes represent an opportunity to provide
9 lanes for transient passing only. In locations where continuous solid lane lines are used to demarcate
10 these special-purpose lanes, inhibition of lane changes is in place. Existing regulatory signing,
11 changeable message signing, and VMS displays can all be used as a platform for a trial passing section in
12 location where demand causes congestion but the fraction of HOV-eligible vehicles is too low to
13 maximize the capacity of the lane.

14 ***Pavement Markings***

15 While pavement markings separating continuing lanes are typically a broken lane line in a ratio of 1:3 or
16 1:4 (e.g., Minnesota), some agencies use dotted lane line patterns and solid lane lines to indicate the
17 intended use of auxiliary lanes. The use of a solid lane line adjacent to the continuing lane alongside a
18 dotted lane line adjacent to an acceleration lane, for example, indicates that crossing into the acceleration
19 lane is discouraged even as vacating the acceleration lane is the intended and necessary maneuver.
20 Research conducted by the Pooled Fund Study⁵ validated the performance of this marking pattern.

21 Use of a solid lane line along the latter distance of truck climbing lanes can likewise discourage
22 movement into the general lanes prior to the crest of a hill. In some selected interchanges, a single solid
23 lane line or even a double solid lane line can be used as a boundary between the left-most lane of a
24 motorway and the remaining lanes.

25 ***Enforcement and Education Campaigns***

26 On motorways today, enforcement activities largely consist of speed interdiction and monitoring of
27 commercial vehicle activities. Traffic data from various agencies indicates a uniform prevalence of
28 speeds above the posted speed limit by non-commercial vehicle operators, a reflection of the human
29 factors challenge associated with blanket speed limits on high-speed roadways. Because these speeds
30 exist and cannot be enforced uniformly and entirely, the promotion of order is best undertaken by law
31 enforcement.

32 A survey of law enforcement agencies was not conducted during the course of this research.
33 However, limited enforcement of lane use courtesy was observed even as speed enforcement activity was
34 reported by media outlets to have declined during a period following early 2020. Correspondingly,
35 researchers observed little investment in traffic safety messages regarding the preservation of order and
36 the availability of the left lane.

37

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1 ***Enforcement of Left Lane Restrictions***

2 In Germany, enforcement of passing restrictions is understood to be aggressive. Use of photo
3 enforcement for speed zones is common on the Autobahn and sections of the Polish Autostrada.
4 Enforcement of passing restrictions for trucks, which are dynamic in Germany by use of the Active
5 Traffic Management System (ATMS) displays and other signing, appears to promote uniform
6 compliance.



7
8 Figure 10 Signing on the Polish Autostrada^k indicates that restrictions on
9 passing by trucks will be enforced using camera systems

10
11 The targeted enforcement section gateway signing displayed in Figure 10 is posted in advance of
12 a section of the motorway passing through a river valley, where dense fog and low visibility are expected.
13 Wet pavement conditions are more likely to occur even when pavement on the approaches to this area are
14 clear and dry. Reserving the left lane for passing by cars only reduces the airborne spray caused by truck
15 tires and reduces the likelihood of a high-speed rear-end collision associated with slower trucks.

16 ***Variable Message Signs***

17 While many jurisdictions limit the use of variable message signs to cogent and pertinent messages, the
18 use of Variable Message Sign (VMS) displays on motorways for traffic safety and statutory reminders
19 continues to grow. Messages such as “CAMP IN THE WOODS / NOT IN THE LEFT LANE” are
20 intended to remind vehicle operators of the requirement to avoid cruising by moving right when finished
21 passing. As with static signing, these messages appeared to be uniformly ignored by vehicle operators.
22 Ignorance of VMS displays and a general unwillingness to display courtesy remain a vexing challenge on
23 motorways under both normal operations and during incidents.

^k European motorway operators use a superior deposition system for pavement markings, visible in this photo, taken approximately 20 minutes after sunset. Of note in the Balkans and in Poland is the use of red reflectors to denote the edges of the roadway, a contrast to the white reflectors used in Germany and utterly inconsistent with the intention of red markers in the United States. These markers do give a U.S.-trained driver pause on the first night!^{SK}

Dynamic Traffic Signing

This research demonstrated the success of active intervention techniques, particularly the use of sequential intermittent activation of the vehicle high beams. This indicates that some vehicle operators will respond to a reminder or request regarding the need to vacate the passing lane and return to the driving lane(s).

Policies regarding the use of static regulatory signing in areas where observed lane use compliance is implicated in operational and safety performance degradation could likewise be applied to dynamic traffic signing. Dynamic traffic signing, that is, signing that displays one or more fixed messages in response to traffic conditions, is commonly used in curve speed warning applications, speed feedback displays, intersection control advance warning signing beacons and displays, and other applications where a change in roadway conditions may not be adequately conveyed using a single fixed-message or static signing.

These systems, intended to alert vehicle operators to the need to maintain lane discipline, referenced here as Lane Use Compliance Information Display (LUCID) systems, would be intended to increase the lucidity of vehicle operators, inducing heightened attention, improved command of the traffic situation, and ongoing compliance in similar settings.

Proposed Sign Messages

The LUCID system is intended to target vehicles approaching VMS installations according to conditional assessment of the traffic composition. LUCID signing could be either display a dynamic message identical to the static signing or display a variety of specialized messages. Three examples of potential messages displayed dynamically are included below.

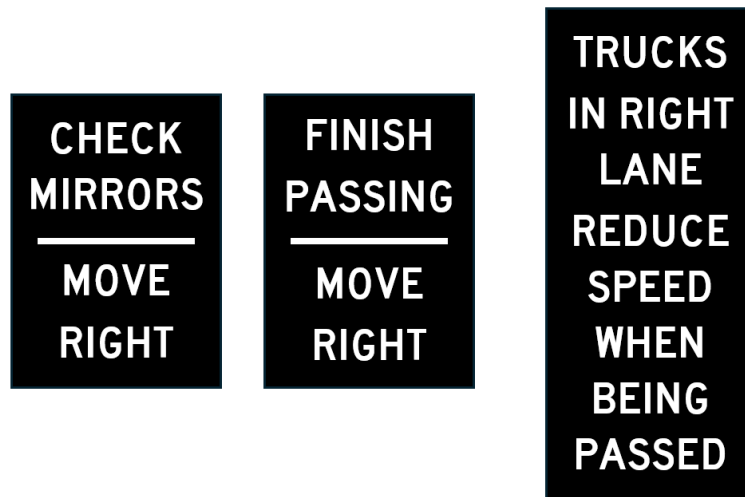


Figure 11 Depictions of displayed word messages in the LUCID System

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LUCID systems could range from simple displays triggered by a narrow-beam radar-based speed reading to a comprehensive system using automatic number plate readers (ANPR) and logic-driven control systems addressing traffic over long distances. The technology integration, concept of operations, and costs are addressed here in a conceptual systems engineering description.

Technology Integration

Dynamic traffic signing for lane use compliance can be deployed using common hardware operating over modern interfaces. Such signs would readily mirror the application of signing for speed feedback displays, which are typically powered by an integrated and often internal battery system that is charged using solar photovoltaic panels. Communications equipment ranges from simple point-to-point systems to remotely-accessible IP-addressable equipment interfacing with a central system via cellular telecommunications systems.

Concept of Operations

The comprehensive LUCID system would operate using ANPR cameras, a central processing system, speed measuring devices, and a sequence of displays. Each target location would feature the full suite of equipment, and information would be shared between locations.

As Level of Service degrades, vehicle operators experience increasing difficulty with maintaining lane use compliance. LUCID system operations would be curtailed when certain conditions prevail, operating according to logic regarding vehicle speeds, density, volumes, and the composition of various vehicle classes in the flow of traffic.

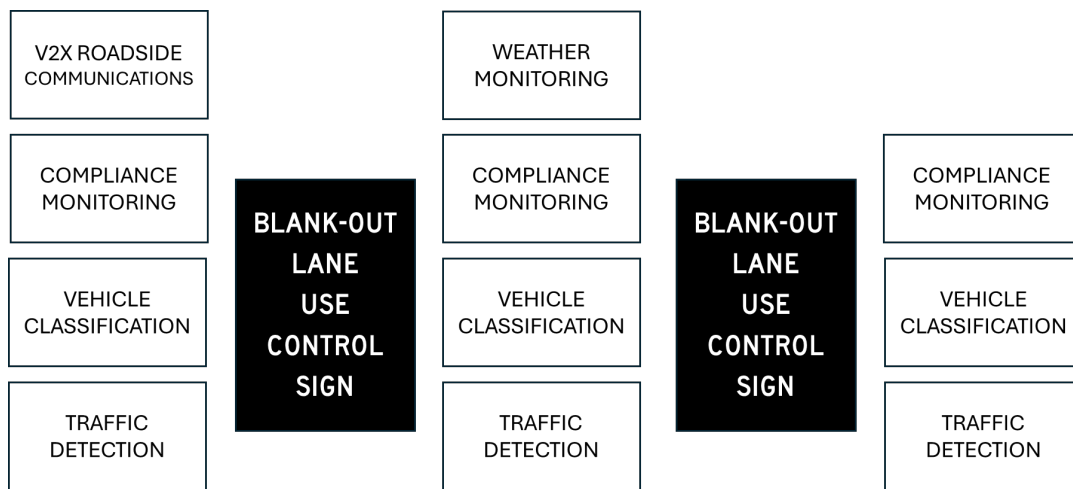


Figure 12 Dynamic Lane Use Compliance Demonstrative System Architecture

1 Privacy Concerns

2 Protecting the liberty of the traveling public must remain the chief goal¹ of all government agencies.
3 While numerous cities use ANPR technology for traffic management activities, strict data protection,
4 retention, and use restrictions exist, an outcome of the European Union’s General Data Protection
5 Regulation.

6 Use of ANPR technology and acquired data for LUCID operations is likely to be considered
7 strictly a driving aid (as is the case with speed feedback displays) and not made accessible for general law
8 enforcement for use in direct punitive actions related to traffic statute violations. It is possible, however,
9 that data from LUCID systems could be used to identify locations where targeted lane use compliance
10 enforcement activities would be most effective.

11 Where data protection and use regulations allow, it is also possible to affect the behavior of repeat
12 offenders, those who repeatedly cruise in the left lane in numerous locations over a period of time, despite
13 receiving LUCID feedback. Such interactions might include courtesy letters or other contact from traffic
14 enforcement personnel. For egregious offenders, site observation and operator contact could lead to
15 driving license actions, arrest, and vehicle impoundment.

16 In sharp contrast to punitive camera systems that use photographs, video, and measurement
17 devices such as lasers to generate citations, the LUCID system would merely inform traffic enforcement
18 personnel of the presence of repeat offenders, allowing for direct contact with a higher probability of
19 corrective action. As with any statutory civil or criminal violation, the strictest standards of due process
20 are applied in order to preserve the integrity of the observation and intervention process, allow for
21 constructive appeals, and demonstrate a corrective impact on traffic operations, safety, and vehicle
22 operator behavior, beginning with the least punitive measures.

23 Capital and Operations Costs

24 The LUCID system could be readily installed without the need for electrical service, wired
25 communications, or other utility expenses. Relying on solar photovoltaic power generation and battery
26 energy storage, some LUCID systems could even be made portable on trailers and moved to sites where
27 surveillance and data analysis indicate that left lane availability is limited by micropassing and blocking.
28 The initial cost for most motorway operators would be software, although ANPR integrations using
29 application process interfaces are likely to become more prevalent.

30

¹ While most agencies would cite “safety” as the chief goal, safety is largely the responsibility of the road user in the context of the designed and built environment. Liberty, defined as the freedom to act responsibly without undue constraints, is always at risk in cultures driven by statistical analysis, which fails to account for individual needs.^{SK}

1 **CONTINUING RESEARCH**

2 This heuristic research activity used engineering analysis and the application of traffic operations theory
3 to validate common cultural perceptions regarding use of the left lane on motorways and high-speed
4 multi-lane divided rural highways. Researchers also identified operational effects of disorder on the
5 motorway, recognizing that motorways where order is prioritized can accommodate unlimited speeds.
6 Additional research can illuminate the opportunities for implementing an order-based approach to
7 statutes, enforcement, education, and in practice on motorways in the United States.

8 **Signing Compliance Assessment**

9 Compliance with existing and proposed regulatory and VMS messages is not well understood, despite the
10 readily-apparent disregard exhibited throughout the period of this assessment. Correlation of compliance
11 with sign presence and sign type, frequency of enforcement, and operational effects of geometric design
12 are present opportunities for further statistical research.

13 **Scenario-Based Speed Compliance Penalties**

14 Recognized already in the reality of the variations in leeway afforded by public safety officers and
15 camera-based revenue generation systems, research into the variability of enforcement effectiveness can
16 help agencies prioritize scarce resources. Scenario-based enforcement would recognize that the speed and
17 flow regimes vary according to Level of Service, ambient conditions, traffic composition, and other
18 factors that influence speed selection such that speeds greater than the posted speed limit do not
19 necessarily indicate that a violation of the intent of the statutes has occurred.

20 **Understanding Regional Behavioral Variations**

21 While obvious differences between Germany and the United States exist with regard to passing behavior
22 on motorways, regional variances throughout the United States and even within states are worthy of
23 additional study. In particular, the impacts of education, enforcement, cultural mores, and road user
24 behavior are not documented in contemporary literature addressing passing behavior on motorways.

25 **Maximizing Use of Special-Purpose Lanes**

26 During off-peak periods, many HOV and High-Occupancy Toll Lane (HOT Lane) facilities could provide
27 for separated lanes dedicated for passing only, for higher speeds, or autonomous vehicles operating
28 according to the basic rule, where minimization of time in the left lane is a primary goal. Field trials
29 using dynamic message signing associated with ATMS deployments can reveal the additional capacity
30 and safety benefits available by using the HOV or HOT network as a part-time passing lane.

31 **Assessing Impacts on Operations**

32 Understanding the effects of blocking and cruising can aid in justifying the implementation of various
33 measures to mitigate inappropriate use of the passing lane. Operations assessments and analysis of
34 motorway operations using probe data, camera-based flow data, and other real-time collection of traffic
35 operations information is likely to reveal regional differences and corroborate with various policy
36 implementations.

1 **Special Enforcement and Education Campaigns**

2 While the effectiveness of emphasis patrols for speed and other behaviors is represented in the literature,
3 a thorough literature review can illuminate opportunities for special-purpose enforcement focused solely
4 on lane use compliance. New technologies supporting less punitive approaches can also aid law
5 enforcement personnel in providing direct contact, education, and written warnings so that repeat
6 offenders are subjected to escalating punishment. Assessing the impacts of enforcement and education
7 campaigns on cultural perception may also provide insights into the general effectiveness of an education-
8 first approach to lane use courtesy.

9 **LUCID Systems Implementation**

10 An intense traffic monitoring system deployment is already being undertaken by Institut für
11 Verkehrssystemtechnik at the Deutsches Centre für Luft um Raumfahrt in Braunschweig, Neidersachsen,
12 Germany. Development and deployment of LUCID systems can allow for further field data collection
13 regarding the effectiveness of systems that also provide detailed information regarding traffic flow.
14 Research on ANPR integration with such systems will be needed to validate system compliance with
15 privacy and security protocols and statutes.

16

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5 perspectives and practices related to passing on motorways, in the United States, Canada, Germany, and
6 Poland.

7 The authors gratefully acknowledge their spouses for the opportunity to discuss following
8 distance, speed, courtesy, and traffic operations theory while operating a motor vehicle or observing the
9 operation of other motor vehicles. These conversations, focused on human factors and observations,
10 mutually benefitted the authors and their spouses, engendering continued growth in a commitment to
11 attentive and courteous driving, demonstrating a personal commitment to traffic safety. As a result of the
12 unusual circumstances incurred during this research, the corresponding author also now recognizes that a
13 raised forward-facing palm means “You are starting to follow too closely for my comfort” without
14 excluding “Yes, you do know what you’re doing because you are a professional, and you are focused on
15 this right now.”

16 The authors gratefully acknowledge every single road user who moved to the right when
17 sufficient headway for rightward vehicles was obtained, thereby increasing the availability of the left lane.
18 Vehicle operators who remained rightward for other vehicles already occupying the left lane are
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24 Transportation Futures is the incubator for the International Motorway Association, with future research
25 available online at <http://marvelousmotorways.org> and in the Association’s biennial publication, *Schnell*.

26

27 COMPLIANCE STATEMENT

28 During the production of the second volume of the *Journal of Traffic Control Device Research*, Scott O.
29 Kuznicki serves as the Managing Editor and was responsible for the production of the *Journal*. As the
30 corresponding author of this paper, Mr. Kuznicki recused himself from all paper review and selection
31 activities associated with the first issue of second volume of the *Journal of Traffic Control Device*
32 *Research*, the document for which this paper was submitted for publication. Similarly, the authors did not
33 request, obtain, or represent special consideration on account of their membership in, participation within,
34 and/or contributions to professional organizations, including Sponsoring Organizations of the National
35 Committee on Uniform Traffic Control Devices.

36

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