

Road Safety Applications vs. Network Constraints: Feasibility Limits of IEEE 802.11p

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Abstract—In the context of vehicular networks, a fundamental trade-off exists between the stringent requirements of road-safety applications and the inherent constraints of the IEEE 802.11p wireless channel. This paper investigates the feasibility limits of such applications by developing analytical models that characterize the interplay between the inter-message gap (IMG), radio parameters, and application requirements. The proposed models are validated through ns-3 simulations, demonstrating a close alignment with theoretical predictions. Our results show that under certain realistic road scenarios, network constraints and safety requirements become mutually exclusive. This leads to the identification of ‘infeasible cases’ where no IMG value can simultaneously satisfy both the target quality of the road-safety application and the channel occupancy limits.

Index Terms—Vehicular Networks, IEEE 802.11p, Road Safety, Head-on Collision Avoidance, Channel Occupancy, Quality of Service.

I. INTRODUCTION

According to the latest annual statistical report on road safety in the European Union (EU) [1], road fatalities remain a critical issue. Despite the continuous integration of advanced safety features by car manufacturers (lane departure detection, forward collision warning...) and the efforts of authorities toward greater safety through stricter regulations — such as the reduction of speed limits, notably the 80 km/h limit on French national roads [2] — the overall decline in deaths has been slow.

To further improve road safety, significant efforts are being made to develop vehicular networks. Wireless technologies are being promoted by organizations such as the IEEE and the 5G Automotive Association (5GAA). To ensure interoperability, European Telecommunication Standards Institute (ETSI) standardizes several families of messages, including Decentralized Environmental Notification Messages (DENM), Cooperative Awareness Messages (CAM), and Collective Perception Messages (CPM). These standards support the implementation of critical safety applications, such as Slow Vehicle Indication, Intersection Collision Warning, and Collision Risk Warning.

However, there is a fundamental trade-off between network constraints and the requirements of road safety applications. These applications include alert broadcasting, complex cooperative services, and the periodic exchange of messages such as, for instance, to extend environmental perception. Taking the latter example on a rural road, the application’s performance

would benefit from the widest possible communication range and the shortest inter-message delay to maximize the probability of alerting an approaching vehicle—and being alerted in return—despite an unreliable network. Conversely, from a network perspective, a shorter range and longer inter-message delays are required to prevent channel saturation, especially when a high volume of messages exchanges occurs.

This article explores application constraints in such emblematic scenarios and simultaneously examines network constraints. We develop a model that identifies satisfactory value ranges for these parameters. We then outline road scenarios in which the values fall outside these satisfactory ranges — in other words, scenarios where the network cannot guarantee the requirements of road safety applications.

The remainder of this paper is organized as follows: Section II reviews related work and positions our contribution. Sections III and IV analyze network and application constraints, respectively. Section V presents numerical results and simulations, highlighting infeasible cases. Finally, concluding remarks end the paper.

II. RELATED WORKS

a) Road safety: The European Road Safety Charter, led by the European Commission, serves as a major collaborative platform for road safety. It is responsible for producing annual statistical reports that monitor fatality and crash trends across the European Union [1]. The scenario selected for this article (rural road) is one of the most accident-prone cases reported herein. In France, the Cerema provides specialized scientific knowledge on accident patterns and driver behavior to inform public policies. A notable example of such work is their comprehensive evaluation of the French government’s decision to lower the speed limit from 90 km/h to 80 km/h on rural two-lane roads starting in July 2018 [2]. In this article, we use data from this report to parameterize our scenario.

b) Vehicular networks: The standardization of Intelligent Transport Systems (ITS) is largely governed by ETSI, which defines several key messaging frameworks to enhance road safety. These include Decentralized Environmental Notification Messages (DENM) for critical road conditions [3], Cooperative Awareness Messages (CAM) for mutual awareness and collision risk estimation [4], and Collective Perception Messages (CPM) for sharing environmental information [5].

Safety applications impose strict network requirements; for example, CAMs typically require transmission periods between 0.1 s and 1 s with a maximum latency of 100 ms [4]. The shortest intervals are mandatory for time-critical services, such as Collision Risk Warning addressed in this paper.

In the ETSI standard, ITS-G5A radio interface uses three 10 MHz channels (5.875–5.905 GHz), with the Control Channel (CCH) dedicated to urgent safety messages [4], [6]. The CAM emission interval is governed by the channel state (Table I), vehicle displacement (every 4 m), and dynamics (changes in direction $\geq 4^\circ$ or speed ≥ 0.5 m/s). We study a steady-state scenario with constant speed and direction.

Messages	CCH channel state Load	Relaxed 0-19 %	Active 19 %-59	Restrictive 59 %-100 %
DP0 (DENM)		50 ms	50 ms	50 ms
DP1 (DENM)		95 ms	190 ms	250 ms
DP2 (CAM)		95 ms	190 ms	250 ms

TABLE I: Smallest time between two messages [6]

c) *IEEE 802.11p capacity*: Wireless technologies for vehicular networks are promoted by organizations such as the IEEE (802.11p) and the 5GAA (5G) [7], [8]. This paper focuses on the IEEE 802.11p standard specifically designed for V2V and V2I communications. The performance of IEEE 802.11p networks has been studied at various levels of granularity. Several works focus on individual link performance, analyzing physical-layer models and MIMO antennas [9], MAC-layer parameters such as contention window size [10], or real-world experimental measurements [11]. This paper instead focuses on network-level performance for a group of vehicles distributed over a geographical area. Furthermore, we specifically consider broadcast transmissions, excluding acknowledgments and retransmissions.

The capacity and reliability of IEEE 802.11p networks have been extensively investigated, with studies focusing on spatial reuse [12], [13] and comparative analyses between 802.11p and LTE-V2V technologies [14]. In contrast, our network-level approach deliberately abstracts radio propagation models and hardware characteristics, such as antenna gains, to depend solely on the number of vehicles within the communication and carrier-sensing ranges.

This simplification enables the derivation of closed-form and invertible expressions for key performance indicators. Such a choice is justified by our objective: identifying the limiting cases of inter-message interval configurations rather than providing a detailed performance evaluation for a specific radio or MAC-layer configuration. Nevertheless, ns-3 simulations demonstrate that the proposed models maintain a high degree of accuracy.

III. NETWORK CONSTRAINTS

A. Introduction

We consider a decentralized radio technology enabling direct vehicle-to-vehicle communications, such as vehicular Wi-Fi based on IEEE 802.11p [7], which is used for the periodic transmission of CAM messages [4]. Let d denote the

transmission duration of a message, excluding channel access delay, and let IMG represent the inter-message gap between two consecutive transmissions. The value of d is determined by the message type and the transmission rate.

We study a uniform road scenario with constant vehicular speeds, where all vehicles periodically transmit messages (e.g., to signal their presence) at a frequency of $\frac{1}{\text{IMG}+d}$. Considering an *ego* vehicle surrounded by N other vehicles (Fig. 1), the input load per period $\text{IMG} + d$ is $(N + 1)d$. To avoid channel saturation, the condition $\frac{(N+1)d}{\text{IMG}+d} < 1$ must be satisfied, which simplifies to $Nd < \text{IMG}$.

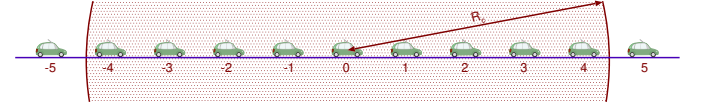


Fig. 1: Uniform road scenario; the ego vehicle numbered 0 can communicate with N ($N = 8$ here) other vehicles within its communication range R_c .

Consequently, if IMG is too short, the channel may become saturated. We therefore derive a lower bound, $\text{IMG}_{\min}$, to ensure that transmissions do not exceed a target channel occupancy ratio $\omega_{\max}$ ($\omega_{\max} \in [0, 1]$), thereby reserving sufficient resources for other coexisting road safety applications.

In our analyses, the radio communication range denoted R_c is assumed to be equal to the frame detection range defined by the Clear Channel Assessment (CCA) mechanism. We neglect CSMA/CA collisions occurring when two vehicles select the same backoff value after sensing an idle channel. However, we account for the more frequent collisions caused by the hidden terminal problem, where vehicles are unable to detect each other's transmissions. The simulations presented hereafter confirm that these approximations do not affect the results.

B. Channel occupancy ratio

We define $\omega_{\text{app}}(\text{IMG})$ as the channel busy time generated by a given road safety application for a specific inter-message gap IMG, computed from the perspective of the ego vehicle at the center (Fig. 1). Note that the application busy time may be lower than the input load because some transmissions overlap.

To estimate this value, we account for transmissions from: i) the clique of vehicles behind the ego vehicle (including itself), ii) the clique of vehicles ahead of the ego vehicle, and iii) the overlaps between transmissions from these two cliques.

The $N/2 + 1$ vehicles of the first clique, numbered from $-N/2$ to 0 in Fig. 1, are within mutual sensing range; consequently, CSMA/CA prevents any overlap between their transmissions, resulting in a total busy time of $d(N/2 + 1)$. Similarly, transmissions from the $N/2$ vehicles of the second clique, numbered from 1 to $N/2$, do not overlap with each other, leading to a busy time of $dN/2$. However, transmissions from the two cliques may overlap. Since a collision can only occur between one vehicle from each clique, at most two transmissions can overlap simultaneously. We compute this overlap as follows.

Let $f(x)$ denote the average overlap duration between a transmission of duration d and another of duration x , both with start times uniformly distributed over the period $[0, \text{IMG} + d]$. Without loss of generality, we fix the start time of the first transmission (duration d) at the beginning of the period (Fig. 2). We then consider different intervals for the start time of the second transmission (duration x). The red part in Fig. 2 corresponds to a complete overlap, with a length of $x - d$. The orange parts correspond to partial overlaps, with a total duration of $2d$. Finally, the green part represents no overlap, with a length of $\text{IMG} - x$. The sum of overlap duration is then equal to $2 \times \int_0^d x \cdot dx + d(x - d) = d \cdot x$. The average overlap duration is then given by:

$$f(x) = \frac{d \times x}{\text{IMG} + d} \quad (1)$$

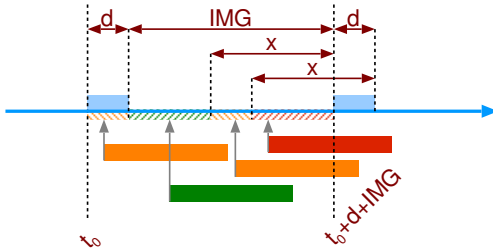


Fig. 2: Red transmission (duration x) completely overlaps with a blue transmission (duration d). Orange transmissions partially overlap, while the green transmission does not overlap. Grey vertical arrows indicate the start times of transmissions within the interval $d + \text{IMG}$.

Since vehicle 1 in Fig. 1 cannot sense the transmissions of vehicle $-N/2$, their transmissions overlap on average by $f(d)$. Similarly, vehicle 2 cannot sense vehicles $-N/2$ and $1 - N/2$, resulting in an average overlap of $f(2d)$, and so on. Thus, the average transmission overlap for vehicle i ($1 \leq i \leq N/2$) is given by $f(i \times d)$. The total overlap is therefore $\sum_{i=1}^{N/2} f(i \times d)$. Consequently, over a period of $\text{IMG} + d$, the medium occupancy ratio $\omega_{\text{app}}(\text{IMG})$ at the ego vehicle for the road safety application is given by:

$$\begin{aligned} \omega_{\text{app}}(\text{IMG}) &= \frac{d \left(\frac{N}{2} + 1 \right) + d \frac{N}{2} - \sum_{i=1}^{N/2} f(i \times d)}{\text{IMG} + d} \\ &= \frac{d(N+1)}{\text{IMG} + d} - \frac{\sum_{i=1}^{N/2} i \times d^2}{(\text{IMG} + d)^2} \\ &= \frac{8d(N+1)(\text{IMG} + d) - d^2 N(N+2)}{8(\text{IMG} + d)^2} \quad (2) \end{aligned}$$

The lower bound on IMG is the value for which the channel occupancy reaches ω_{max} , i.e., $\omega_{\text{app}}(\text{IMG}) = \omega_{\text{max}}$. From Eq. 2, we obtain a quadratic equation with the following two roots:

$$\text{IMG}_{\min} + d = \frac{8d(N+1) \pm \sqrt{\Delta}}{16\omega_{\text{max}}}$$

with $\Delta = 64d^2 \left(\frac{(2-\omega)}{2} N^2 + (2-\omega)N + 1 \right)$.

We have $\Delta > 0$ and we observe that the first root consistently yields an input load exceeding 1. Consequently, the second root is retained:

$$\text{IPG}_{\min} = \frac{d(N+1) + d\sqrt{\frac{(2-\omega)}{2} N^2 + (2-\omega)N + 1}}{2\omega} - d \quad (3)$$

IV. APPLICATION CONSTRAINTS

A. Road safety scenario

In the context of road safety, V2V communication supports various applications; this work focuses specifically on head-on collision avoidance. This application requires a bidirectional exchange of messages between two vehicles approaching from opposite directions. For the application to be successful, this exchange must be completed while the inter-vehicle distance remains between the communication range R_c and the warning distance R_w (Fig. 3).

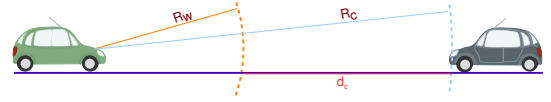


Fig. 3: V2V scenario for prevention head-on collision

A lower bound on R_w can be estimated by considering the minimum bumper-to-bumper stopping distance, which is determined by the vehicle speed, driver reaction time, and braking distance. Taking into account the relative vehicle speeds, the distance $R_c - R_w$ defines a critical communication time t_c , during which at least one message from each vehicle must be successfully received. Consequently, a larger R_c and a shorter IMG increase the probability of application success.

As an illustration, let consider a numerical application. We focus on rural roads, where the proportion of fatalities is particularly high [1]. Based on [2], we consider a vehicle speed $S = 90$ km/h, accounting for the fact that many drivers exceed the 80 km/h limit by 10 % or more. As the observed driver reaction time typically varies between 1.5 and 3.5 seconds depending on age and distraction, we adopt a value of $\sigma = 3$ s for our scenario, which corresponds to a distance of approximately 75 m. The emergency braking distance is calculated for a horizontal road using a constant deceleration $f = 7$ m/s² (noting that this factor depends on speed, road quality, tire condition, weather...), resulting in $S^2/2f \simeq 45$ m. Consequently, the total stopping distance is estimated at approximately 240 m, which defines the smallest warning radius R_w . With a communication range of $R_c = 400$ m, the communication time is $t_c = (R_c - R_w)/(2S) = 3.2$ seconds.

B. Upper Bound on the inter-message-gap

In the head-on collision avoidance scenario, the application requires at least one message to be successfully received by both vehicles during the interval t_c . To ensure this, we derive an upper bound IMG_{max} , as an excessively large inter-message gap would compromise application success. Since

these broadcast messages lack an Automatic Repeat Request (ARQ) mechanism, the probability of non-reception equals the frame error rate (FER), necessitating multiple transmissions to guarantee success. Assuming constant and equal IMG, the number of possible transmissions within t_c is $\frac{t_c}{\text{IMG}+d}$.

We denote by q the application-level quality, defined as the probability that two vehicles located within the region between R_c and R_w successfully receive at least one message from each other. We assume that message losses are independent and identically distributed with probability denoted $\lambda(\text{IMG})$ to explicitly reflect its dependence on the inter-message gap. The probability that all messages transmitted by the first vehicle are lost is $\lambda(\text{IMG})^{\frac{t_c}{\text{IMG}+d}}$. Consequently, the probability that at least one message is successfully received is $1 - \lambda(\text{IMG})^{\frac{t_c}{\text{IMG}+d}}$. Assuming reciprocal reception and independent losses in both directions, we obtain:

$$q = \left(1 - \lambda(\text{IMG})^{\frac{t_c}{\text{IMG}+d}}\right)^2 \quad (4)$$

The above expression can be rearranged to express IMG as a function of the other parameters. We define a function $g(x)$ such that $\text{IMG}_{\max}$, the largest inter-message gap satisfying a given quality requirement q , is the solution to the fixed-point equation $g(x) = x$:

$$g(x) = \frac{\ln(\lambda(x))}{\ln(1 - \sqrt{q})} t_c - d \quad (5)$$

C. Loss rate estimation

As a first approximation, the loss rate is estimated based on potential collisions generated by the road safety application (head-on collision avoidance), without accounting for other traffic occupying the remaining $1 - \omega$ of the channel. This approach leads to an underestimation of the actual loss rate. To estimate $\lambda(\text{IMG})$, we examine collisions at the ego vehicle's position in the scenario depicted in Fig. 1. Transmissions from vehicle $-N/2$ may collide with those of vehicle 1. More generally, transmissions from vehicle i ($1 \leq i \leq N/2$) may collide with those from vehicles $-N/2$ up to $i - N/2$ at the position of the ego vehicle. For these vehicles, channel access attempts are not governed by the CSMA/CA mechanism because they originate from outside the CCA region (see Section III-A).

Assuming that each such attempt is uniformly distributed over the interval $[0, \text{IMG} + d]$, the collision-free interval is $\text{IMG} - d$ (green interval in Fig. 4). Consequently, the probability of no collision, denoted by a , is given by:

$$a = \frac{\text{IMG} - d}{\text{IMG} + d} \quad (6)$$

As vehicle i in Fig. 1 may collide with i vehicles (from $-N/2$ to $i - N/2$), its probability of transmitting without causing a collision at the ego vehicle's position is a^i . The average message loss rate is then obtained by averaging over all values of i from 1 to $N/2$. We obtain:

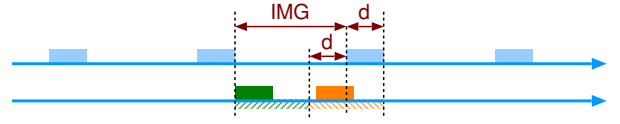


Fig. 4: Considering the periodic transmissions of a vehicle (blue), another vehicle must select its transmission time within the green interval to avoid a collision. A transmission time selected within the orange interval results in a collision.

$$\begin{aligned} \lambda(\text{IMG}) &= 1 - \frac{1}{\frac{N}{2}} \sum_{i=1}^{\frac{N}{2}} a^i \\ &= 1 - \frac{\text{IMG} - d}{dN} \left(1 - \left(\frac{\text{IMG} - d}{\text{IMG} + d}\right)^{\frac{N}{2}}\right) \end{aligned} \quad (7)$$

V. NUMERICAL RESULTS

A. Model validation

The validity of the previously derived formulas is evaluated through ns-3 simulations. We consider the V2V scenario described in Fig. 3, with varying vehicle densities $N \in \{24, 50, 74, 100\}$ as shown in Fig. 1. The simulation parameters implemented in ns-3 are summarized in Table II.

TABLE II: ns-3 simulation parameters.

Parameter	Value
ns-3 version	ns-3.46
PHY standard	IEEE 802.11p
Data rate	3 Mbps
Radio range R_c	400 m
CCA detection range	400 m
Message duration d	0.0006 s
Simulation time	11 s

The channel busy time generated by our road safety application, $\omega_{\text{app}}(\text{IMG})$, is presented in Figure 5. The results of Equation 2 align well with the ns-3 simulations, except under very high network load (excessively small IMG values, which are not of practical interest considering N). The average error computed over all IMG values is 2%.

Figure 6 compares the theoretical loss rate λ derived from Equation 7 with the results obtained through ns-3 simulations. The model aligns closely with the observed packet loss behavior, with a mean error of 0.8%. This error is expressed as the mean absolute difference between the theoretical model and the simulation results. These findings confirm the validity of our model and the assumptions presented in Sec. III-A.

B. Parameters study

Figure 7 presents a realistic parameters configuration for the rural road scenario (Fig. 3). The loss rate $\lambda(\text{IMG})$ and the observed quality are plotted in orange and brown, respectively, according to Eq. 7 and Eq. 4. The minimum IMG required to avoid network saturation is indicated by a vertical line in light blue according to Eq. 3 ($\text{IMG}_{\min} = 317$ ms). The maximum

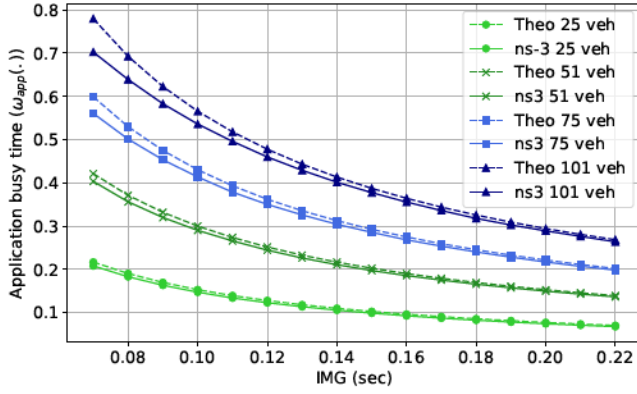


Fig. 5: Theoretical vs. simulated channel busy time of the application $\omega_{app}(IMG)$ for various vehicles densities.

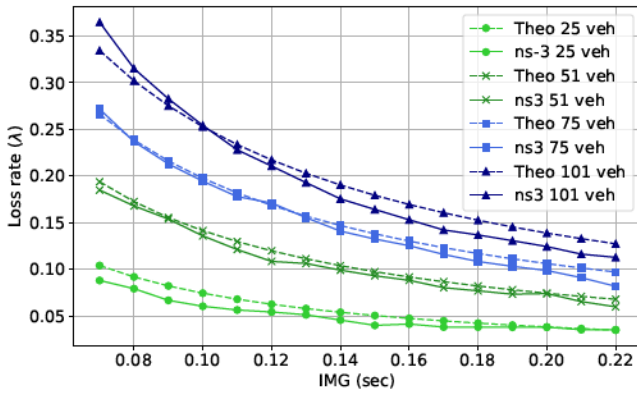


Fig. 6: Theoretical vs. simulated loss rate $\lambda(IMG)$ for various vehicles densities.

IMG ensuring the success of the head-on collision avoidance application is indicated in dark blue ($IMG_{max} = 800$ ms); it is determined as the solution to the fixed-point equation $g(x) = x$ (Eq. 5), where $g(x)$ is plotted in green. For all $IMG \leq IMG_{max}$, the observed quality remains above the target q , with $q = 0.99$ reached exactly at $IMG = IMG_{max}$.

The target channel occupancy ω_{max} is set to 0.2 to reserve capacity for emergency traffic. Decreasing ω_{app} would shift IMG_{min} to the right on the graph. Under the ETSI standard with this network load (Sec. II and Table I), the bounds would be $ETSI_{min} = 190$ ms and $ETSI_{max} = 1$ second indicated by dashed vertical lines (during the 55 m braking distance, IMG reaches its minimum due to deceleration, see Sec. II). When the vehicle's speed increases, the communication time t_c is reduced, then shifting IMG_{max} to the left of the graph ($t_c = 1.31$ sec at 100 km/h compared to 3.2 sec at 90 km/h).

Extending the communication range R_c increases the window t_c , but also increases the number of neighboring vehicles, which in turn raises IMG_{min} . We denote by N_a the *additional vehicles* outside the ego vehicle's lane that remain within R_c and implement the same application. Fig. 7 is plotted with

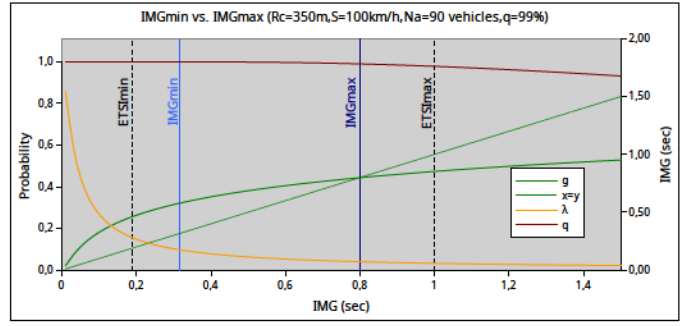


Fig. 7: An example of configuration for the rural road scenario.

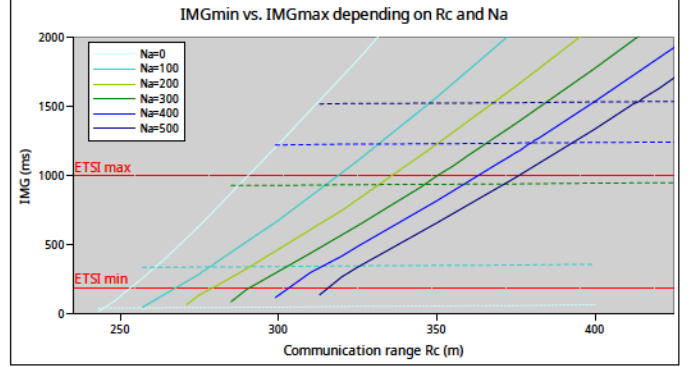


Fig. 8: IMG_{min} and IMG_{max} as a function of R_c and N_d .

$N_a = 90$, corresponding for instance to an exit lane with dense traffic and an average speed of approximately 20 km/h.

Figure 8 plots IMG_{min} and IMG_{max} as a function of R_c for several values of N_a . As R_c increases, both IMG bounds shift toward larger values — particularly IMG_{min} — eventually exceeding the ETSI limits (indicated in red).

C. Infeasible Cases

We investigate infeasible cases, i.e., realistic road traffic situations in which network and application requirements cannot be simultaneously satisfied. Mathematically, this occurs when the upper bound imposed by the application constraints is lower than the lower bound imposed by the network constraints ($IMG_{max} < IMG_{min}$). Such cases are observed in Fig. 8 for certain combination of R_c and N_i .

Tables III and IV report the maximum number of additional vehicles N_a for $q = 0.99$ and $q = 0.999$, respectively. This value is defined as the number of interfering vehicles for which the upper and lower bounds of IMG coincide. Any further increase in the number of interfering vehicles results in the violation of at least one constraint, such as the application quality requirements or the channel occupancy limitations.

For instance, with $\omega_{app} = 0.2$ and $q = 0.99$, Table III shows that the maximum number of additional vehicles within the communication range is 463 for the rural scenario (cell highlighted in blue). Such a situation may occur when a road runs parallel to or intersects a congested four-lane highway with an inter-vehicle spacing of 7 m. Here, $R_c = 400$ m although

TABLE III: Infeasible cases $q = 0.99$.

Scenario	$\omega_{app} = 0.38$	$\omega_{app} = 0.2$	$\omega_{app} = 0.1$
Rural	$N = 21$ $N_a = 678$ IMG = 1.05	$N = 21$ $N_a = 463$ IMG = 1.41	$N = 21$ $N_a = 286$ IMG = 1.82
Urban	$N = 35$ $N_a = 1212$ IMG = 1.87	$N = 35$ $N_a = 828$ IMG = 2.52	$N = 35$ $N_a = 513$ IMG = 3.24

TABLE IV: Infeasible cases $q = 0.999$.

Scenario	$\omega_{app} = 0.38$	$\omega_{app} = 0.2$	$\omega_{app} = 0.1$
Rural	$N = 21$ $N_a = 466$ IMG = 0.73	$N = 21$ $N_a = 316$ IMG = 0.98	$N = 21$ $N_a = 193$ IMG = 1.27
Urban	$N = 35$ $N_a = 833$ IMG = 1.30	$N = 35$ $N_a = 565$ IMG = 1.75	$N = 35$ $N_a = 346$ IMG = 2.26

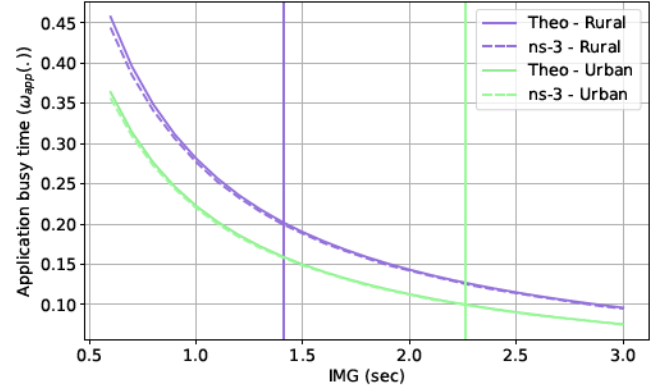
larger communication ranges would make this threshold even easier to exceed. For the urban scenario, with $\omega_{app} = 0.1$ and $q = 0.999$ (cell highlighted in green), such a situation is highly plausible at roundabouts or road intersections.

These two specific cases (the rural and urban scenarios, corresponding to the blue and green cells, respectively) were simulated using ns-3. Figure 9 depicts the application busy time as a function of the Inter-Message Gap (IMG). The vertical lines at 1.41 and 2.26 indicate the specific IMG values for which both the network and application constraints are simultaneously satisfied. For instance, in the rural scenario, an IMG value of 1.41 yields exactly the target application busy time of 0.2. A smaller IMG would violate the channel occupancy constraint, whereas a larger IMG would compromise the quality requirement q (not shown in the figure). In these scenarios, an increase in the number of additional vehicles (N_a) leads to an infeasible case, where no value of IMG can satisfy both the q and ω_{max} constraints.

VI. CONCLUSION

In this paper, we combined the requirements of a critical road safety application — specifically head-on collision avoidance — with network constraints through several analytical models. These models enabled us to derive operational bounds for the inter-message gap (IMG), ensuring both the success of the application and the maintenance of a target channel occupancy ratio. A key finding of this work is that, in many realistic scenarios, the optimal IMG values diverge from the recommendations issued by ETSI. Moreover, our analysis allowed us to identify the feasibility limits of this application within a regular scenario (uniform vehicle distribution and constant speed), highlighting specific cases where network constraints and safety requirements become mutually exclusive.

Future work will account for variable IMG values in dynamic scenarios involving changing directions or speeds, which may necessitate higher sending frequencies according to ETSI standards. A natural extension of this research would be the design of application-layer mechanisms capable of dynamically adapting transmission frequencies, even in highly

Fig. 9: Application busy time ($\omega_{app}(\text{IMG})$).

congested scenarios. Such a mechanism would adjust the IMG according to the real-time road traffic situation and the criticality level of the application, thereby optimizing the balance between safety guarantees and network stability.

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