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Regression-based Evaluation of Novel Intensity Measures under Alternative Ground Motion Record Sets

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Regression-based Evaluation of Novel Intensity Measures under Alternative Ground Motion Record Sets

K Kadas[1] and A Yakut[2]

[1] Scientific Project Specialist, Middle East Technical University, Ankara, Türkiye
[2] Professor, Middle East Technical University, Ankara, Türkiye

E-mail: ayakut@metu.edu.tr

Abstract. Intensity measures are generally considered as the fundamental properties of strong ground motion records and are widely utilized in performance-based seismic design methodology to relate the seismic hazard levels to the structural damages, or seismic response in general. Recent two decades have exhibited several studies proposing new alternatives that have intended to reduce the variability in seismic demand predictions. Although there exist several simple-to-advanced scalar and vector ground motion intensity measures; the literature is limited in the number of comparative studies investigating the efficiency of these parameters, especially in the entire response range of structures. This study aims at evaluating the correlation of major engineering demand parameters with novel simple-to-advanced intensity parameters following a regression-based approach to calculate efficiency metrics. For a group of low- to relatively high-rise reinforced concrete frames, alternative ground motion record sets have been formed considering different simple scalar intensity measures including peak ground acceleration, peak ground velocity, acceleration spectrum intensity, velocity spectrum intensity and spectral acceleration at the fundamental period of the structure of consideration, and utilizing these record sets, nonlinear time history analyses have been performed using OpenSees software to obtain key engineering demand parameters of the multi-degree-of-freedom systems. The correlation performance of novel scalar and vector intensity parameters have been quantified by evaluating regression models formed in between demand parameters and intensity measures. The regression-based approach has assisted to rank the ground motion intensity parameters according to their efficiency in terms of reducing the variability in response. The results of this comprehensive study display the relative correlation performance of scalar and vector forms together and mark particular scalar parameters as 'best candidates' for reliable loss estimation studies, despite their simplicity.

1. Introduction

The reliability of technical evaluations made throughout the steps of performance-based seismic design and assessment methodologies is particularly based on the accurate relation of the seismic hazard levels to the structural damages, or seismic responses in general. To achieve this goal, practitioners of the earthquake engineering field had mostly referred to the fundamental properties of strong ground motion records, which are generally termed as intensity measures (IMs). Among well-known intensity measures, peak ground acceleration (PGA) and peak ground velocity (PGV) are the peak values directly obtained from the acceleration or velocity trace, whereas a structure-specific alternative -the spectral acceleration at the fundamental period of the structure, $S_a(T_1)$- requires the calculation of the response spectrum. Obviously, there exist several other simple parameters that display the characteristics of the strong motion records, yet have received criticism from the experts. Consequently, the need for better alternatives as opposed to simple intensity measures to reduce the variability in seismic demand predictions has motivated the researchers of the field and eventually, recent two decades have exhibited several studies proposing several simple-to-advanced scalar and vector ground motion intensity measures. On the contrary, the literature is limited in the number of comparative studies investigating the efficiency of these parameters, especially in the entire response range of structures. This study aims at evaluating the correlation of major engineering demand parameters (EDPs) with novel simple-to-advanced intensity parameters following a regression-based approach to calculate efficiency metrics, that display the performance of the questioned parameter. To accomplish this, a group of low- to relatively high-rise reinforced concrete frames have been subjected to alternative ground motion record sets to perform nonlinear time history analyses in order to obtain key engineering demand parameters of the multi-degree-of-freedom systems. The relative correlation performance of novel scalar and vector intensity parameters have been quantified by evaluating regression models formed in between demand parameters and intensity measures.

2. Background and Intensity Measures Considered

Seismic intensity indices have evolved from simple peak value-based scalar forms into compound and/or more advanced scalar as well as vector intensity measures with two or more parameters due to the poor performance of the simple forms to characterize the damage potential of the ground motions on the structures. Correspondingly, a relatively broad list of research studies [1-15] have concentrated on the comparative evaluation of the intensity parameters to display their correlations with certain engineering demand parameters. Among these scientific endeavors, the studies by Yılmaz [2], Yakut and Yılmaz [3] and Kadas and Yakut [8] have especially concentrated on the performance of intensity indices in the entire response range of the structures they examined, and shown the superiority of certain indices as opposed to their counterparts, but remained limited in terms of the consideration of recently proposed scalar or vector intensity measures. This study establishes on the recommendations of the previous study by Kadas and Yakut [8] and extends the correlation performance evaluations by incorporating a larger list of intensity measures which will be described next.

Kadas and Yakut [8] has already examined almost 30 IMs with single-degree-of-freedom (SDOF) based analyses, and led to a shortlist of scalar IMs such as peak ground acceleration (PGA), peak ground velocity (PGV), Arias Intensity (AI), Specific Energy Density (SED), Cumulative Absolute Velocity (CAV), a modified version of Acceleration Spectrum Intensity (ASI*), Velocity Spectrum Intensity (VSI), Fajfar Index (I_F), Riddell and Garcia Index for Velocity region (I_v), Spectral acceleration at the fundamental period - $S_a(T_1)$ for further consideration in multi-degree-of-freedom (MDOF) system-based analyses and these IMs have been directly included in this study as well. Besides, ASI and HI have been also considered herein as alternatives to ASI* and VSI. Additionally, scalar Effective Peak Acceleration (EPA), Effective Peak Velocity (EPV), improved definitions of EPA and EPV (IEPA and IEPV) [16] have been included in the list. Apart from these scalar forms, recently proposed scalar and vector IMs that particularly consider structure-specific forms have been added to the study list. These spectra-based parameters are listed in Table 1 to explicitly present the assumed values for certain parameters in the relevant formulations. Finally, vector IMs formed either with PGV/PGA ratio (for consideration of frequency content) or significant duration ($t_{5\text{-}95}$) (for consideration of the ground motion duration) have been included into the final list. It would be important to note here that these final vector IMs have been formed considering PGA, PGV, ASI, ASI*, VSI, HI, and $S_a(T_1)$, alternatively, as the primary IM. The complete list of IMs examined within the context of this study contains 39 IMs in total.

Table 1. Abridged list of additional major IMs considered

Intensity Measure with Reference	**Description - Mathematical Formulation**
Scalar IM by Cordova et al. [17]	$S_{aC} \equiv S_a(T_1)\left\{\frac{S_a(2T_1)}{S_a(T_1)}\right\}^{0.5}$ where required parameters are as c=2.0 and α=0.5
Scalar IM by Lin et al. [18]	$S_{aCM} \equiv S_a(T_1)\left\{\frac{S_a(1.5T_1)}{S_a(T_1)}\right\}^{0.5}$ where required parameters are as c=1.5 and α=0.5
Scalar IM by De Biasio et al. [19]	$ASA_{40}(T_1) = 2.5T_1 \int_{T_1}^{1.67T_1} \frac{S_{pa}(T,\xi)}{T^2}\,dT$
Vector IM by Bojórquez & Iervolino [20]	$\left\{\begin{matrix} S_a(T_1) \\ N_p \end{matrix}\right\}$ where $N_p = \frac{S_{a_{avg}}(T_1,\ldots,2T_1)}{S_a(T_1)}$
Scalar IM by Bojórquez & Iervolino [21]	$I_{N_p} = S_a(T_1){N_p}^{0.40}$
Vector IM by Baker & Cornell [22]	$\left\{\begin{matrix} S_a(T_1) \\ R_{T_1,T_2} \end{matrix}\right\}$ where $R_{T_1,T_2} = \frac{S_a(2T_1)}{S_a(T_1)}$
Vector IM by Theophilou et al. [23]	$\left\{\begin{matrix} S_a(T_1) \\ S_{dN}(T_1,T_2) \end{matrix}\right\}$ where $S_{dN}(T_1,T_2) = \frac{1}{S_d(T_1)T_N}\int_{T_1}^{T_2} S_d(T)\,dT,\quad T_1 < T_2 \text{ and } T_N = 1.0\ s$
Vector IM by Yakhchalian et al. [24][25]	$\left\{\begin{matrix} S_a(T_1) \\ S_a(T_1)/_{DSI} \end{matrix}\right\}$ where DSI has been considered as the area under the elastic spectral displacement between T=2.0 sec and T=5.0 sec.

3. Description of Alternative Ground Motion Record Sets and Frames

It has been previously shown by the former study [8] that the IM considered in the formation of a ground motion record affect the correlation performance of any IM evaluated with reference to the selected engineering demand parameters, and has recommended ASI*, VSI and $S_a(T_1)$ parameters to be considered in the compilation of alternative ground motion sets so that less dispersion could be obtained in seismic demand predictions. This study follows this recommendation and utilizes five alternative ground motion record sets, considering PGA-based and PGV-based set formations as well. In the formation of sets, a main strong ground motion database (i.e., Pacific Earthquake Engineering Research Center's (PEER) 2005 Ground Motion database) has been utilized to select 110 records at most for the IM considered with a stratified random sampling approach, where the maximum value for the selected intensity parameter is defined by the main database's maximum values. Selection of 11 records per stratum is based on the recommendation of relevant NIST [26] report. General features of the alternative record sets are displayed in Figure 1, whereas the reader is referred to [8] and [27] for further details regarding the ground motion record sets (please note that S_a-based sets' features are not shown here due to space limitations).

These alternative record sets have been employed to perform nonlinear time history analyses via OpenSees software [28] on MDOF models of a group of low- to relatively high-rise reinforced concrete frames (with fundamental periods ranging from 0.30 to 1.20 sec). The structural details regarding the frames can be found in [29].

4. Regression-based Evaluation of Selected Intensity Measures

4.1. Description of the Evaluation Methodology

The choice of the "best candidate" intensity measure(s) from a list of competitors, which is a fundamental step in performance-based earthquake engineering, necessitated the establishment of competency criteria and has brought *efficiency, sufficiency, practicality, scaling robustness,* and *hazard computability* concepts into the picture [27]. Among these criteria, *"Efficiency"* is simply defined as the capability to reduce the variability in the EDPs obtained from the analyses, thus allowing to reduce the number of GM records to be utilized or the number of analyses to be performed for a target accuracy level. Formerly, the efficiency criterion was implicitly being investigated through correlation statistics in terms of Pearson or Spearman statistics and the calculation was straightforward for scalar type IMs. However, with the introduction of vector IMs, the in-depth evaluation of the statistical distribution of EDPs at specific IM levels to reveal the efficiency characteristics of the subject IM necessitated a common statistical approach that will be applicable to both scalar and vector IM cases. The probabilistic seismic demand models, which are defining the relationship between IM and structural responses (i.e., EDPs) in a probabilistic manner, utilize rigorous analysis techniques to derive the statistical characteristics. Stripe Analysis, Multiple Stripe Analysis, and Cloud Analysis mainly constitute the advanced solutions to the problem, where the Cloud Analysis mostly employs a set of unscaled records to achieve a seismic demand model.

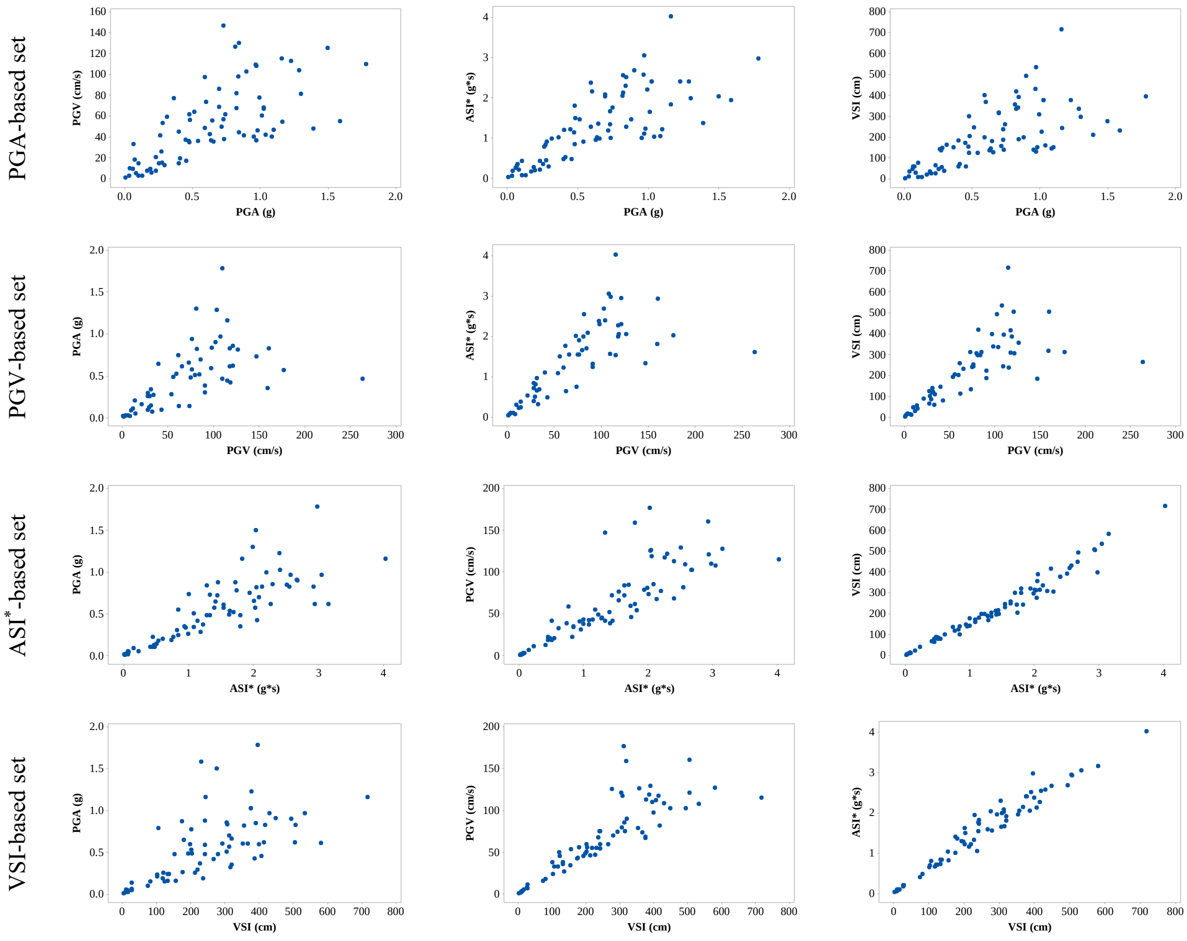

Figure 1. General features of the alternative ground motion record sets

Established upon the fundamentals of cloud analysis approach, this study utilizes a linear seismic demand model assuming a log-normal distribution of the related random variables ([30],[31]). In both equations, the uncertainty in the seismic demand due to record-to-record variability is reflected through the ε parameter, which is a log-normal random variable with a median 1.0 and logarithmic standard deviation $\sigma_{ln\varepsilon} = \beta_{EDP|IM}$ or $\sigma_{ln\varepsilon} = \beta_{EDP|IM_1\&IM_2}$.

Scalar IM case: $ln(EDP) = \beta_0 + \beta_1 ln(IM) + \varepsilon$ (1)

Vector IM case: $ln(EDP) = \beta_0 + \beta_1 ln(IM_1) + \beta_2 ln(IM_2) + \varepsilon$ (2)

MATLAB software [32] has been utilized to perform the regression studies (in between IMs and selected EDPs namely top displacement-TD, maximum inter-story drift ratio-MIDR and base shear-BS) to derive the linear demand models, and a list of statistical metrics have been computed to quantify the quality of the alternative regression models. To evaluate the efficiency of the scalar intensity measures along with their vector rivals, a performance parameter (similar to Pearson correlation coefficient in the case of correlation studies) was needed. Among the statistical metrics computed, the **R^2-adjusted value** corresponding to each regression model has been considered as the best simple metric to establish a common ground for comparisons. This is a modified version of regression statistic **R^2 (coefficient of determination)** that accounts for the increasing nature of R^2 when there are extra explanatory variables added to the regression model (as in the case of two-predictor models). This metric is considered to be more appropriate (with respect to R^2 metric) while evaluating a model fit in comparison with alternative models, and a value close to 1.0 designates the superiority of the model. The text will keep the focus on the evaluation of performance of alternative IMs according to **R^2-adjusted values** due to space limitations, thus; the reader is referred to [27] for further details regarding the evaluation of the quality of the alternative regression models.

The regression studies including R^2-adjusted value computations have been performed for 7 frames, 3 different EDPs (TD, MIDR and BS), 39 IMs under 5 different ground motion record sets (where the IM considered for the formation of each set, **DB IM**, is as PGA, PGV, ASI*, VSI and $S_a(T_1)$, alternatively). For each frame-DB IM-EDP case, the IMs have been sorted according to decreasing values of R^2-adjusted values so that the better performing candidate IMs have been ranked in the top. The detailed tables have been later simplified, as displayed in Table 2, in order to clearly show the performance of specific 15 IMs with their rankings and R^2-adjusted values together. These IMs have been selected from the list of 39 IMs due to the fact that they are either widely used scalar IMs *-PGA and PGV-*, better candidates *-ASI*, VSI, $S_a(T_1)$, ASI, HI-* or a qualifying list of S_a-based scalar and/or vector intensity measures -S_{aC}, Sa_{CM}, ASA_{40}, I_{N_p}, $\langle S_a, R(T_1,T_2)\rangle$, $\langle S_a, N_p\rangle$, $\langle S_a, S_{dN}\rangle$, $\langle S_a, S_a/DSI\rangle$). As it can be inferred from Table 2 (exemplifying only the cases of F2S2B2 frame with the shortest fundamental period and F8S3B frame with relatively long fundamental period), **top 5 ranking IM** cases in each row have been marked with **bold fonts**. These summary tables have been also visualized to display the period-wise variation of efficiency performances, and Figure 2 exemplarily shows the graphical results for MIDR cases occurring under 5 alternative GM record sets, where the bar colors darken with increasing fundamental period.

4.2. Discussion of the Results

TD-based charts (which could not be presented within the manuscript due to space limitations) and MIDR-based charts (Figure 2) have marked the superiority of the novel scalar and vector IM candidates over the ordinary scalar indices, which was expected due to the fact that these more recent candidates are S_a-based and structure-specific. When the evaluations are comparatively made among the TD- and MIDR-based results of ordinary scalar IMs, S_a is the best parameter in most of the cases. PGA and ASI turned out to be relatively more efficient for the short period system, ASI being slightly superior. The relatively high efficiency of these two parameters rapidly diminished with increasing periods. PGV exhibited comparably low performance at short periods, while its performance has much improved beyond the short period range. As opposed to PGA, PGV, and ASI, spectrum-based (but structure-independent) ASI* and VSI turned out to be much more stable in terms of efficiency in the entire period range considered. ASI* was slightly superior at short periods, while VSI enhanced its performance at longer periods. HI also showed a high correlation at long periods, but its performance is lower with respect to VSI at short-to-medium periods, but outperforms VSI at long periods. The less preferred parameter EPA has shown a slightly higher correlation with respect to PGA for the short-period system, but did not outperform ASI. The modified version of EPA, IEPA, exhibited higher efficiency with respect to PGA, but failed to perform better as opposed to the original EPA, while for medium-to-long period systems, IEPA showed relatively higher efficiency. The results for medium period systems have revealed the superiority of the velocity-based EPV with respect to PGV (even

VSI in specific cases), whereas the performance of IEPV was mostly close to PGV. Correspondingly, IEPV, as a recommendation of Yang et al. [16] for near-fault ground motions, did not bring in additional improvement to the efficiency with respect to its counterparts. The performances of AI, SED, CAV, I_F, and I_v will not be re-discussed here, as interpretations about these alternative scalar IMs are consistent with the outcomes of the former study [8].

When the R^2-adjusted based evaluations are extended to the spectrum based novel IMs, it has been observed that these more advanced parameters mostly ranked in the top 15 with R^2-adjusted values above 0.94 and generally close to each other, and the performances seemed to be comparatively constant in the period range of consideration. The numerical values for TD- and MIDR-based results have marked the superiority of ASA_{40} with respect to both scalar and vector forms, yet there are few cases where other novel candidates took the lead as well. The relatively better performance of ASA_{40} has confirmed the suitability of R=40 assumption for the structure set used herein. On the contrary, S_{aC} and S_{agm} yielded slightly lower values with respect to original S_a in general (with particular exceptions), pointing to the inappropriate period assumptions for cT_1 and $T^{(n)}$ input parameters in these IMs. S_{aCM}, in contrast, performed comparably better with respect to S_{aC}, indicating that the input parameters (c and α) recommended by Lin et al. [18] are more appropriate for the systems analyzed (and for the IM formulation). In the vectorial forms $\langle S_a, N_p\rangle$ and $\langle S_a, R(T_1, T_2)\rangle$, the same T_2 was assumed (i.e., $T_2 = 2T_1$) and the performance metrics had the same order of magnitude. Although $\langle S_a, N_p\rangle$ had been proposed as a better indicator of the spectral shape (for the period range defined) as opposed to $\langle S_a, R(T_1, T_2)\rangle$ ([20],[21]), this phenomenon was not observed numerically herein. However, both IMs performed better than the scalar S_{aC}. Even the scalar alternative of $\langle S_a, N_p\rangle$, I_{N_p}, generally performed relatively better than S_{aC}, while this simpler version yielded slightly lower values in general with respect to the original form. The last two IMs in the summary list, $\langle S_a, S_{dN}\rangle$ and $\langle S_a, S_a/DSI\rangle$), require more complex calculations with respect to $\langle S_a, R(T_1, T_2)\rangle$ and other advanced scalar indices as they employ displacement spectrum as well, but generally yielded higher R^2-adjusted values.

It would be beneficial to re-express that all these S_a-based advanced scalar and vector parameters rely on assumed input parameters to calculate the defined indices, and further calibration of these numerical inputs (for each structural system or for the whole building set) might lead to increased efficiencies (i.e., R^2-adjusted values) and eventually, modify rankings of the top IMs. Nevertheless, it can be principally stated that $\langle S_a, R(T_1, T_2)\rangle$ and $\langle S_a, N_p\rangle$ are the most efficient vector IMs herein along with their relative simplicity as opposed to $\langle S_a, S_{dN}\rangle$ and $\langle S_a, S_a/DSI\rangle$. Further significance checks for the second parameter of these vector IMs, on the other hand, have occasionally raised concerns about the statistical significance of the secondary indices within the regression models.

When the vector IMs with consideration of frequency content or significant duration (i.e., $\langle IM_1, PGV/PGA\rangle$ or $\langle IM_1, t_{5-95}\rangle$ classes) are examined (though not presented in summary tables), it has been frequently observed that PGV/PGA or $t_{5\text{-}95}$ seem to slightly enhance the R^2-adjusted based efficiency performance of vector IMs with respect to their corresponding scalar IM_1 cases, yet supplementary statistical parameters did not always confirm that these improvements are statistically significant. PGV/PGA turned out to be more influential while supplementing poor-performing PGA or ASI, while remained with limited impact in vector forms with PGV, VSI, HI, ASI* and $S_a(T_1)$. The duration-related parameter $t_{5\text{-}95}$, in contrast, was relatively less effective for the structural systems considered.

Table 2. Overall summary of efficiency rankings with respect to R^2-adjusted values (frames F2S2B2 and F8S3B).

F2S2B2 (0.30s)

Adjusted-R^2 Summary

EDP	DB IM	1-PGA	2-PGV	6-ASI*	7-VSI	10-Sa	11-ASI	12-HI	17-SaC	18-SaCM	20-ASA40	21-INp	36-Sa, R(T1,T2)	37-Sa, Np	38-Sa, SdN	39-Sa, Sa/DSI
TD	**PGA**	31-0.841	33-0.818	21-0.91	27-0.863	*8-0.97*	17-0.93	34-0.792	12-0.951	**2-0.973**	**1-0.979**	*10-0.967*	**3-0.972**	*6-0.972*	**4-0.972**	**5-0.972**
	PGV	19-0.943	35-0.725	26-0.907	30-0.86	*6-0.983*	11-0.979	32-0.811	16-0.968	**3-0.983**	**1-0.989**	*7-0.983*	**5-0.983**	**4-0.983**	**2-0.984**	*10-0.983*
	ASI*	21-0.952	33-0.865	26-0.931	30-0.897	*10-0.979*	12-0.977	35-0.857	17-0.971	14-0.977	**1-0.985**	*9-0.979*	**3-0.981**	**4-0.981**	**5-0.981**	**2-0.981**
	VSI	21-0.933	33-0.797	27-0.891	32-0.827	*8-0.972*	12-0.967	34-0.787	17-0.948	*10-0.968*	**1-0.978**	15-0.965	**2-0.976**	**3-0.975**	**5-0.974**	**4-0.975**
	Sa	22-0.92	33-0.831	25-0.908	31-0.857	*7-0.973*	13-0.954	34-0.79	19-0.935	11-0.954	*6-0.973*	15-0.951	**2-0.975**	**1-0.975**	**3-0.974**	**5-0.974**
EDP	**DB IM**	**1-PGA**	**2-PGV**	**6-ASI***	**7-VSI**	**10-Sa**	**11-ASI**	**12-HI**	**17-SaC**	**18-SaCM**	**20-ASA40**	**21-INp**	**36-Sa, R(T1,T2)**	**37-Sa, Np**	**38-Sa, SdN**	**39-Sa, Sa/DSI**
MIDR	**PGA**	29-0.858	33-0.817	23-0.907	30-0.856	*9-0.967*	15-0.941	34-0.782	13-0.948	**3-0.971**	**1-0.975**	**5-0.968**	*6-0.968*	*8-0.967*	**2-0.972**	**4-0.969**
	PGV	19-0.945	35-0.727	27-0.906	30-0.858	**3-0.983**	11-0.979	32-0.809	16-0.967	*10-0.982*	**1-0.987**	*9-0.982*	*6-0.983*	**5-0.983**	**2-0.985**	*8-0.983*
	ASI*	21-0.955	33-0.866	26-0.93	31-0.895	11-0.979	12-0.979	35-0.855	17-0.971	15-0.977	**1-0.984**	*6-0.98*	**5-0.981**	*8-0.98*	**3-0.982**	**4-0.982**
	VSI	21-0.937	33-0.801	27-0.892	32-0.828	*9-0.971*	12-0.969	34-0.789	17-0.95	13-0.968	**1-0.977**	15-0.966	**3-0.975**	**5-0.974**	**2-0.976**	**4-0.975**
	Sa	22-0.92	33-0.821	25-0.898	31-0.845	*6-0.971*	11-0.953	34-0.776	19-0.93	15-0.95	*8-0.969*	16-0.949	**3-0.972**	**2-0.973**	**1-0.975**	**5-0.971**
EDP	**DB IM**	**1-PGA**	**2-PGV**	**6-ASI***	**7-VSI**	**10-Sa**	**11-ASI**	**12-HI**	**17-SaC**	**18-SaCM**	**20-ASA40**	**21-INp**	**36-Sa, R(T1,T2)**	**37-Sa, Np**	**38-Sa, SdN**	**39-Sa, Sa/DSI**
BS	**PGA**	33-0.828	31-0.835	17-0.908	27-0.868	11-0.931	21-0.898	34-0.81	*8-0.936*	**3-0.944**	**2-0.947**	*6-0.938*	**5-0.939**	*7-0.937*	**1-0.973**	**4-0.944**
	PGV	21-0.924	34-0.759	24-0.907	29-0.865	*8-0.959*	12-0.951	32-0.825	15-0.95	*10-0.957*	**2-0.964**	*9-0.957*	**4-0.96**	*6-0.96*	**1-0.987**	**3-0.961**
	ASI*	26-0.933	32-0.894	23-0.941	31-0.913	12-0.96	15-0.956	35-0.881	*8-0.965*	*9-0.963*	**5-0.968**	*6-0.965*	*7-0.965*	*10-0.963*	**1-0.986**	**3-0.972**
	VSI	22-0.927	33-0.842	25-0.92	31-0.87	18-0.938	13-0.943	34-0.835	14-0.943	*9-0.947*	**5-0.953**	16-0.942	**4-0.956**	*8-0.949*	**1-0.979**	**3-0.956**
	Sa	22-0.876	33-0.762	27-0.85	31-0.791	**3-0.94**	*10-0.925*	34-0.72	17-0.899	16-0.919	*8-0.938*	14-0.92	**4-0.94**	**2-0.941**	**1-0.975**	*6-0.94*

F8S3B (1.20s)

Adjusted-R^2 Summary

EDP	DB IM	1-PGA	2-PGV	6-ASI*	7-VSI	10-Sa	11-ASI	12-HI	17-SaC	18-SaCM	20-ASA40	21-INp	36-Sa, R(T1,T2)	37-Sa, Np	38-Sa, SdN	39-Sa, Sa/DSI
TD	**PGA**	39-0.525	29-0.881	28-0.884	20-0.922	**4-0.982**	38-0.586	15-0.969	14-0.97	*10-0.977*	*9-0.981*	**3-0.983**	*8-0.982*	**5-0.982**	**1-0.986**	**2-0.983**
	PGV	36-0.775	22-0.924	25-0.911	19-0.934	**5-0.966**	38-0.727	13-0.956	16-0.947	11-0.957	*6-0.966*	*10-0.961*	**2-0.97**	**3-0.968**	*7-0.966*	**1-0.972**
	ASI*	37-0.778	28-0.929	29-0.926	19-0.948	*8-0.982*	39-0.75	14-0.971	11-0.977	*10-0.981*	**2-0.984**	*6-0.983*	**4-0.984**	**5-0.983**	**3-0.984**	**1-0.986**
	VSI	36-0.761	23-0.946	27-0.93	18-0.961	12-0.971	39-0.701	11-0.971	17-0.962	**4-0.974**	**1-0.977**	**3-0.975**	**5-0.973**	*8-0.972*	*10-0.972*	**2-0.977**
	Sa	36-0.713	27-0.925	28-0.923	20-0.95	*9-0.972*	39-0.679	14-0.967	15-0.964	**5-0.974**	**2-0.98**	*10-0.972*	**3-0.976**	**4-0.975**	11-0.972	**1-0.98**
EDP	**DB IM**	**1-PGA**	**2-PGV**	**6-ASI***	**7-VSI**	**10-Sa**	**11-ASI**	**12-HI**	**17-SaC**	**18-SaCM**	**20-ASA40**	**21-INp**	**36-Sa, R(T1,T2)**	**37-Sa, Np**	**38-Sa, SdN**	**39-Sa, Sa/DSI**
MIDR	**PGA**	39-0.628	25-0.921	19-0.944	*7-0.968*	17-0.95	38-0.694	**4-0.976**	23-0.924	21-0.937	20-0.939	18-0.949	12-0.955	*9-0.96*	14-0.953	16-0.95
	PGV	33-0.837	25-0.924	20-0.947	*10-0.961*	11-0.961	38-0.787	**1-0.967**	23-0.929	19-0.947	17-0.954	16-0.955	14-0.96	15-0.96	*9-0.961*	*7-0.961*
	ASI*	37-0.849	23-0.96	12-0.967	*7-0.981*	16-0.965	39-0.823	**2-0.984**	28-0.951	26-0.958	20-0.963	21-0.963	18-0.965	17-0.965	15-0.965	14-0.965
	VSI	36-0.805	22-0.953	21-0.956	*7-0.976*	14-0.966	39-0.749	**2-0.977**	27-0.945	15-0.965	*9-0.968*	*10-0.968*	16-0.965	18-0.965	12-0.968	13-0.966
	Sa	36-0.754	25-0.936	22-0.944	19-0.965	*10-0.971*	39-0.712	*6-0.973*	20-0.956	*8-0.971*	**2-0.976**	*7-0.972*	*9-0.971*	11-0.971	14-0.971	**4-0.974**
EDP	**DB IM**	**1-PGA**	**2-PGV**	**6-ASI***	**7-VSI**	**10-Sa**	**11-ASI**	**12-HI**	**17-SaC**	**18-SaCM**	**20-ASA40**	**21-INp**	**36-Sa, R(T1,T2)**	**37-Sa, Np**	**38-Sa, SdN**	**39-Sa, Sa/DSI**
BS	**PGA**	39-0.672	12-0.932	*10-0.937*	*6-0.946*	25-0.9	38-0.738	*7-0.945*	29-0.894	26-0.899	28-0.898	21-0.907	27-0.899	23-0.901	15-0.93	24-0.9
	PGV	35-0.794	16-0.906	11-0.922	*7-0.93*	20-0.898	37-0.792	**5-0.934**	23-0.894	28-0.885	25-0.892	24-0.893	17-0.906	19-0.898	**1-0.95**	15-0.91
	ASI*	37-0.826	12-0.939	11-0.943	*9-0.951*	25-0.928	39-0.819	**3-0.955**	27-0.923	28-0.922	22-0.929	26-0.927	20-0.93	23-0.929	*6-0.955*	18-0.933
	VSI	36-0.802	*8-0.932*	16-0.925	**3-0.934**	23-0.905	39-0.768	11-0.929	29-0.893	28-0.894	25-0.902	26-0.898	20-0.908	22-0.905	**1-0.957**	18-0.911
	Sa	36-0.729	23-0.89	21-0.901	18-0.916	**5-0.935**	39-0.721	*10-0.926*	13-0.924	17-0.917	*8-0.934*	14-0.921	**3-0.944**	**4-0.941**	**1-0.958**	**2-0.947**

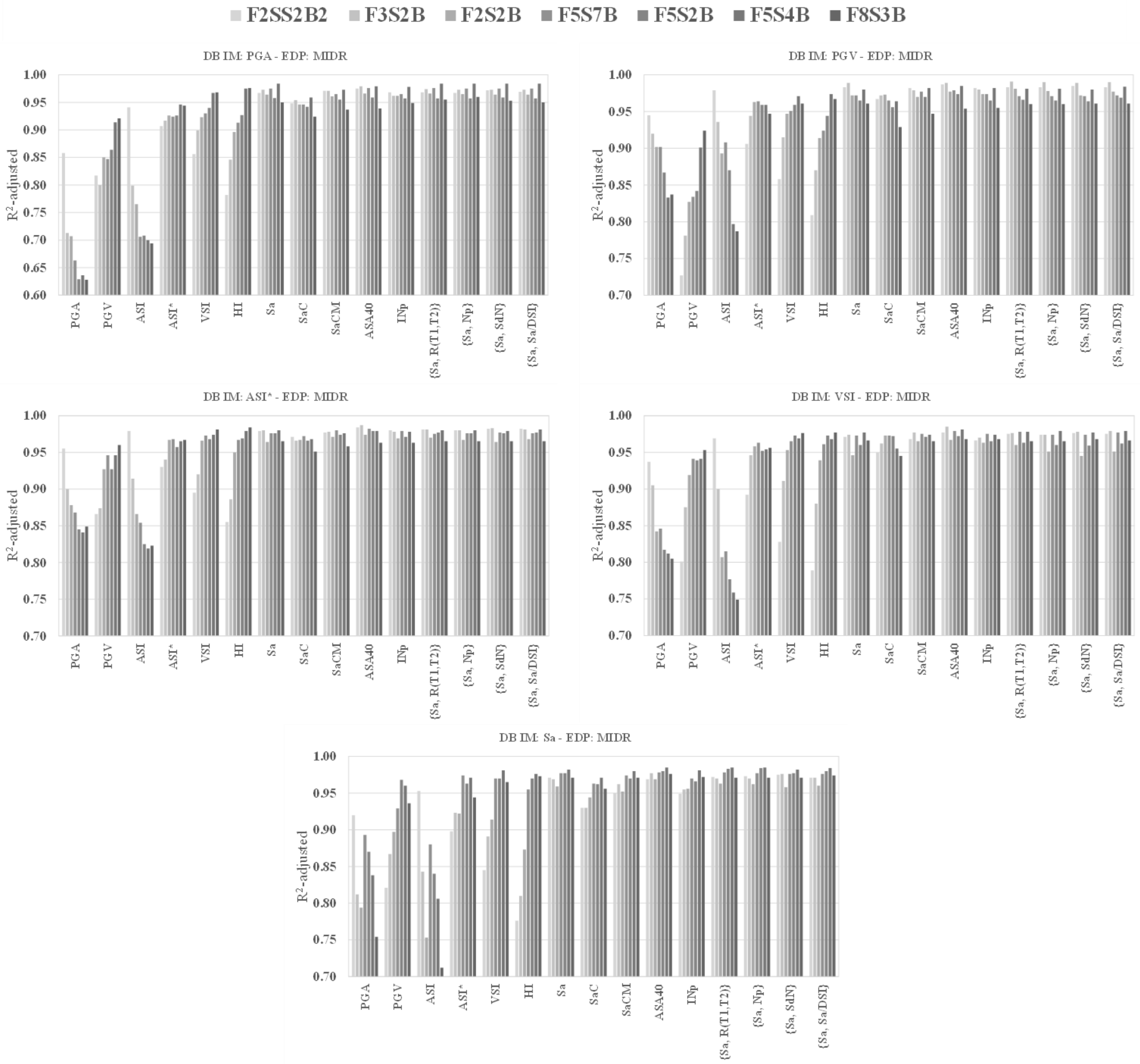

Figure 2. Period-wise variation of R^2-adjusted values for MIDR under alternative GM sets

In comparison with TD- and MIDR-based evaluations, BS-based performance metrics mostly turned out to be lower for top-performing scalar or vector IMs, whereas for poor-performing IMs, some improvements with respect to TD- or MIDR-based statistics have been observed especially for the PGA-based GM set. Among the IMs presented in the summary tables, the vector IM $\langle S_a, S_{dN} \rangle$ mostly outperformed in BS-based cases, while the detailed examination of additional statistical metrics corresponding to this IM has raised concerns about the validity of its superior performance.

GM set-wise comparative evaluation of efficiency metrics has revealed that the performance of acceleration-related indices improved with the utilization of PGV- based GM set with respect to the PGA-based results. On the contrary, PGV-based set yielded lower values for PGV (with the exception of the case for the long-period system) when compared with the PGA-based results. It has also been observed that choosing ASI* and VSI as DB IM improved the R^2-adjusted statistics of PGA, PGV, ASI*, and VSI where the improvement for PGA case remained limited with respect to others. When the efficiency metrics for S_a and other novel scalar-vector IMs are examined, DB IM did not seem to change the performance of these candidates significantly.

5. Conclusions

A regression-based evaluation study has been undertaken to examine the efficiency performances of novel intensity measures in comparison with the well-known scalar forms considering the entire response range of selected moment resisting frames. Linear seismic demand models have been formed utilizing the nonlinear time history analysis results obtained under alternative ground motion record sets, and statistical metrics (R^2-adjusted values, specifically) have been computed and monitored to rank a long list of scalar and vector IMs to display the relative correlation performance of candidates. Overall examination of the efficiency metrics has highlighted the superiority of structure-specific S_a and S_a-based scalar/vector IMs while predicting frame-based TD, MIDR and BS demands. When the focus is directed to S_a and S_a-based novel IMs, S_a clearly exhibited higher efficiency with respect to ordinary scalar IMs. In the meantime, among the more advanced forms, ASA_{40}, $\langle S_a, R(T_1, T_2)\rangle$, $\langle S_a, S_{dN}\rangle$, $\langle S_a, S_a/DSI\rangle$, and $\langle S_a, N_p\rangle$ generally performed better than S_a, while introducing additional computational cost. It has been observed for particular cases that supplementary statistical metrics raise concerns about the statistical significance of the secondary IM in these vectorial forms. The high performance of ASA_{40} along with its simplicity (though necessitates the consideration of the period elongation) puts forward this IM among the novel IM candidates. The vector IMs in combination with ordinary scalar IMs and PGV/PGA or $t_{5\text{-}95}$ have occasionally performed slightly better than their corresponding scalar forms, while PGV/PGA-based alternatives seemed to be more effective herein with respect to duration related $t_{5\text{-}95}$.

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